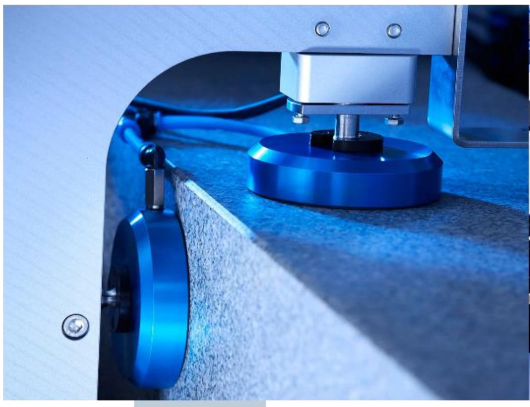
Air Bearing Design and Application Guide



Last update: 2023-06-07

Table of Contents

Last update: 2023-06-07

Last update: 2023-06-07

PART I: UNDERSTANDING AIR BEARINGS

1 Introduction

Bearing technology represents an age-old problem for mechanical engineers and machine designers. Rolling element bearings developed in the last century were a revolutionary improvement over plain bearings (simply a shaft rotating inside a housing) which had been pushed to their limits by applications like early electric motors and automobile engines. In a similar fashion in the 21st century, rolling bearings are being pushed to their limits by the demands of modern precision applications like semiconductor manufacturing, high resolution scanning, and nanometer accurate high speed tooling.

Air bearings represent the next logical step in bearing design, moving from contact motion to frictionless motion on a micro thin layer of air. Air bearings as a whole have a proven track record of being used in coordinate measuring machines for over 20 years, and their advantages are numerous. From near zero friction to hysteresis free motion and absolutely zero need for lubrication, air bearings offer powerful advantages to today's machine designers. To date, these benefits haven't been fully utilized, as air bearings are difficult to manufacture, and were not, historically, commercially available. Supplier IBS Air Bearings was founded in 1992 to pioneer the use of porous media technology and provide the market with robust, simple to use, inexpensive and standardized air bearing products.

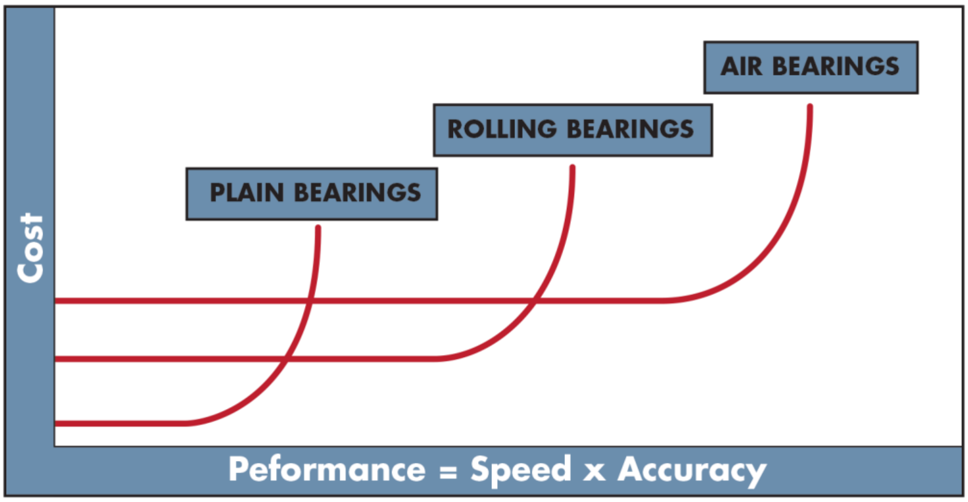


Figure 1 Bearing Performance vs. Cost

The purpose of this guide is to answer the most common questions designers have when first considering porous media air bearings, as well as providing detailed information to help ensure the successful adoption and integration of our technology into your application.

Last update: 2023-06-07

2 What is an Air Bearing?

Unlike contact roller bearings, air bearings utilize a thin film of pressurized air to provide a frictionless load-bearing interface between two surfaces which would otherwise contact each other. Since air bearings are a non-contact technology, they avoid long-standing tribological problems like friction, wear and the necessity for lubrication. This set of traits provides air bearings with unique advantages for precision positioning and high speed applications, among many others.

The air bearing's fluid film is achieved by supplying a flow of air through the bearing face and into the gap between the bearing and the guide surface. This is typically accomplished by pushing the air through a series of orifices or a porous media substrate, which acts to restrict or meter the flow of air into the gap (Figure 2). This restriction is designed such that the outflow of air through the gap is equal to the inflow through the bearing surface, and thus creating a constant fluid film layer. This same restriction maintains pressure under the bearing and acts as the load bearing surface. If air were introduced into the gap without restriction, fly height and air consumption would both be higher than necessary, and stiffness would be lower than that which could be achieved with proper restriction. This restriction is referred to as air bearing compensation, and is used to optimize the bearing with respect to load, lift and stiffness for each individual application. Porous media compensation will be discussed later in more detail.

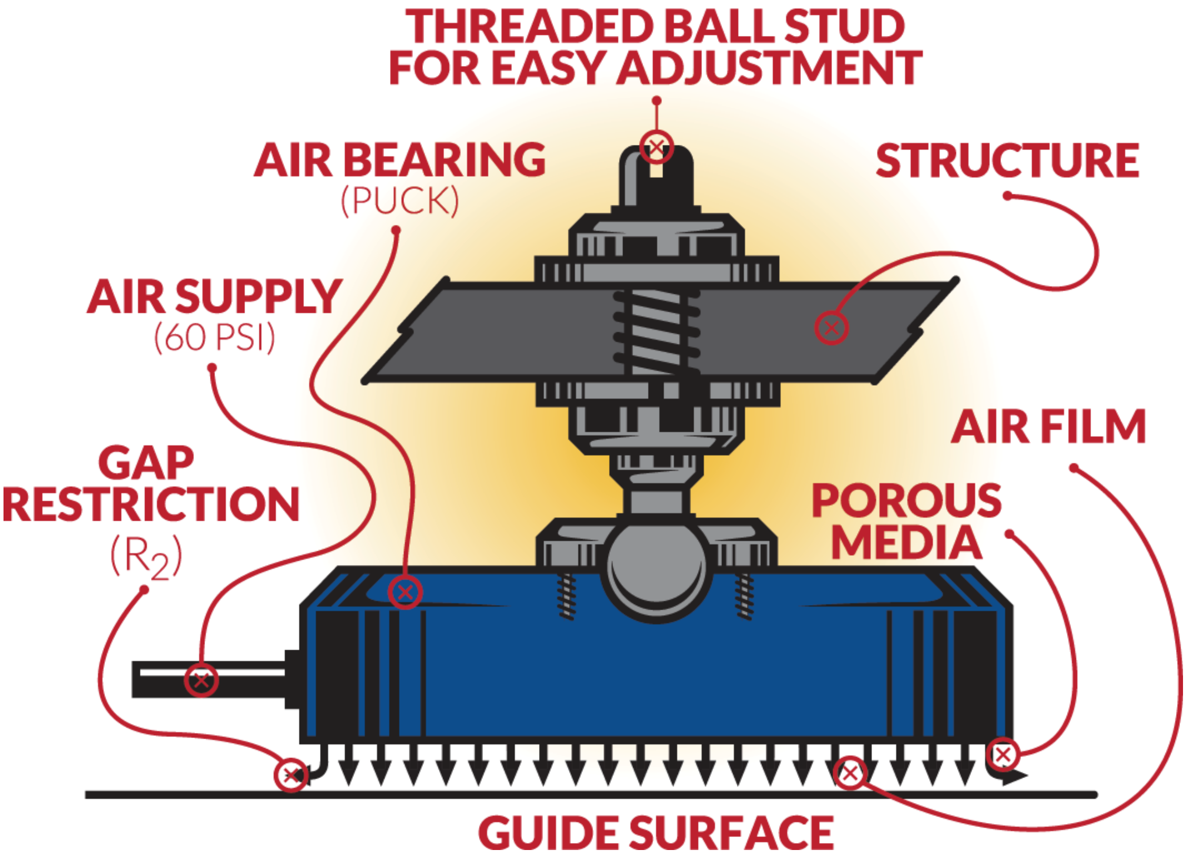


Figure 2 Flat Air Bearing

Last update: 2023-06-07

3 Why use Air Bearings?

Owing to the numerous advantages offered over rolling element bearings, air bearings are a natural choice for applications such as coordinate measuring machines, precision machine tools, semiconductor wafer processing and other applications requiring a combination of high speed, repeatable motion and cleanroom compatibility. The main advantages to air bearings are listed below, and some of the main concerns a design engineer might raise (friction, wear, stiffness and load capacity) are then discussed in more detail.

Zero Friction

Because air bearings have zero static friction, this enables infinite resolution of motion that is highly repeatable.

ZERO WEAR

Non-contact motion means virtually zero wear owing to friction, resulting in consistent machine performance and minimal particulate generation.

STRAIGHTER MOTION

Rolling element bearings are directly influenced by surface finishing and irregularities on the guide surface. The air bearing's fluid film layer averages these errors resulting in straighter motion.

SILENT AND SMOOTH OPERATION

Recirculating rollers or balls create noise and vibration as hard elements are loaded, unloaded and change directions in return tubes. Air bearings have no dynamic components resulting in virtually silent operation.

HIGHER DAMPING

Being fluid film bearings, air bearings have a squeeze film damping effect resulting in higher dynamic stiffness and stability.

No Lubrication

Air bearings do not use or need oil, and thus eliminates the need for lubrication. In dusty environments like dry machining, the positive air pressure from the bearing self-cleans the guideways, compared to oil which can collect contaminants and cause even more wear and tear.

Last update: 2023-06-07

3.1 Friction

Variance in friction has always been a problem at the heart of precision positioning, especially when starting or stopping motion. This is especially pronounced in plain bearings, but also in rolling bearings, where the static coefficient of friction is higher than the dynamic coefficient of friction. In other words, it takes more force to initiate motion than it does to maintain motion. Consider the example of a motor turning a screw to push a slide, Due to static friction, the screw winds up and stores some of the energy in the slide. Once the slide begins to move, the frictional coefficient drops off and the screw unwinds, pushing the slide past it's desired position. This phenomenon is known as "stick slip" and is most pronounced in plain way systems. Stick slip can manifest in multiple kinds of systems, and is capable of causing positioning and bandwidth issues even in machines with rolling element bearings.

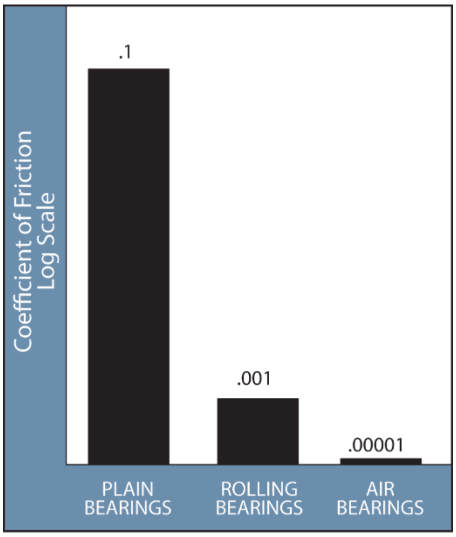


Figure 3 Coefficients

Today, heavy machine tools can be positioned to within 0.001" using rolling element bearings, due to the minute differential between static and dynamic coefficients of friction; an order of magnitude less than the difference for plain journal bearings. However even rolling element bearings are being pushed to their limits. In some areas of the electronics industry, for example, even a positioning tolerance of 0.0001" (or one ten thousandth of an inch) is considered to be too coarse. Rolling element bearing manufacturers have started reducing their preload (and in the process compromising stiffness) in what's known as the "california fit", in an effort to meet these requirements. Unfortunately even with reduced preload, the california fit can only be so effective.

In an air bearing, there is no difference between the static and dynamic coefficients of friction, so the stick slip issue is completely eliminated. Friction in air bearings is a function of air shear, which is itself a function of motion. Therefore at zero velocity there is zero friction, making infinite resolution of motion theoretically possible.

Friction also has a direct effect on efficiency, and the reduction of friction has long been a driving force behind the development of air bearings. George Westinghouse (1846-1914), the American industrialist most well-known for his invention of the locomotive air brake and financing Nikola Tesla during the infamous "war of the currents" against Thomas Edison, filed and received one of the first patents for an air bearing, with the intent of integrating it into a vertical steam driven turbine for generating power. Westinghouse recognized that because air has a viscosity several hundred times lower than that of oil, he could use air as a working fluid and reduce energy lost to oil shear. Unfortunately for Westinghouse, the manufacturing techniques available to him at the turn of the twentieth century made it exceedingly difficult to manufacture large bearing surfaces to the degree of precision the technology requires, since a bore and shaft require a 0.0005" gap to properly function. Even today, large turbines still use oil based hydrodynamic bearings, but many newer microturbines on the market are adopting aerodynamic bearings to improve efficiency. This is a market IBS Precision Engineering is actively evaluating for the adoption of our products, and we see great potential for it.

Friction also affects precision through thermal expansion. Friction leads to heat; for example, a spindle being heated will grow axially, and as the heat conducts into the headstock, it will expand and the centre of rotation will grow away from the base. For a given application, an air bearing will create significantly less heat than a rolling element or plain bearing. Air bearings are still capable of generating heat, but they need to exceed speeds in excess of 100 feet per second before any substantial heat can be generated or measured.

Last update: 2023-06-07

3.2 Wear

Mechanical wear is another thorn in the side of a design engineer. Advanced machines are requiring faster speeds and higher reliability. In fact, some machines on the market can make upwards of one billion moves per year. For machines like this accelerated testing is impossible and design engineers are forced to rely on projections to calculate speed, acceleration and loading requirements for the bearings these tools will operate upon.

Due to their non-contact nature air bearings avoid this problem. Air bearings are immune to conventional modes of wear when operating normally, and will perform exactly the same in the tenth year of operation as they did in the first, even after a billion cycles per year. Neither speed, loading nor acceleration causes wear on an air bearing's surface, and as such has no influence on the life of the bearing. The primary mode of wear on an air bearing is erosion of the bearing surface, and so the quality and cleanliness of your air supply has the greatest effect on the life of the bearing.

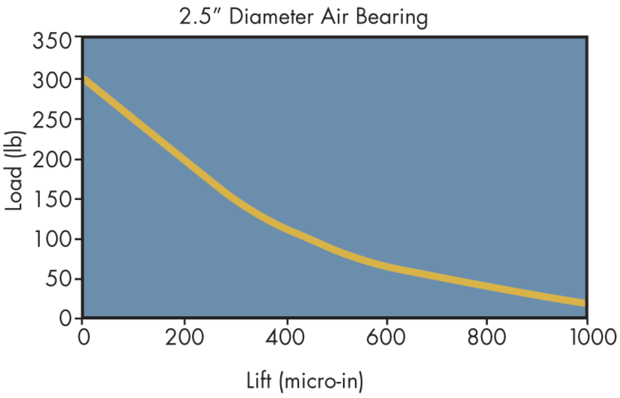
The lack of wear and tear offers a large advantage when it comes to machine reliability. Original Equipment Manufacturers, or OEMS, can say to their customers that wear has been eliminated, removing one more variable capable of affecting your statistical process model and thus providing a distinct competitive advantage.

Because air bearings don't degrade from contact wear and tear and thus don't require lubrication, they are ideally suited for use in cleanroom, medical, pharmaceutical and food processing applications. Furthermore, due to the positive pressure which self-cleans the bearing surface, air bearings excel in dry, dusty environments like salt or sugar factories, which might otherwise be highly corrosive to contact bearings systems. In particulate-laden environments, any lubrication quickly becomes a lappy slurry, while the air bearing's self-purging effect blows away dust and other light particulates.

Last update: 2023-06-07

3.3 Stiffness

A common misconception regarding air bearings is that they do not have the stiffness necessary for precision applications. This couldn't be further from the truth. A 6 inch diameter bearing operating at 60 psi can produce a stiffness in excess of 2,000,000 lb/in under a 1,000 lb loading. This works out to less than a millionth of an inch of deflection per pound of additional force. In Figure 4, you can observe a lift/load curve for an air bearing, which measures the change in air gap as a function of various loadings. Observing Figure 4, we see that air bearings do not have a linear stiffness curve but rather an exponential one, producing higher and higher stiffness values as the film becomes thinner and the loading becomes higher. This is owed to the squeeze film effect, a powerful phenomenon which provides air bearings with many of their unique traits. Pressure and surface area both have proportional relationships to stiffness, but the most significant factor in air bearing stiffness is the utilization of compensation.



Lift load curves are useful for sizing air bearings. Notice also that the slope of the curve is representative of bearing stiffness. A vertical line would represent infinite stiffness and a horizontal line would represent zero stiffness.

$$\text{Stiffness} = \frac{\Delta \text{Load}}{\Delta \text{Lift}}$$

Load (lb)	Lift (micro-in)	ΔLoad	ΔLift	Stiffness (lbs/in)	Compliance (micro-in/lbs)
100	450				
		25	90	277,778	3.6
125	360				
		25	60	416,667	2.4
150	300				
		25	50	500,000	2.0
175	250				
		25	50	500,000	2.0
200	200				

The stiffness between any two points on the curve in figure 2 can be calculated as shown. Stiffness is typically expressed in pounds per inch units, but it is more intuitively obvious when described in micro inch per pound terms. So rather than saying a bearing has 500,000 lbs/in stiffness we may say it will displace two micro inches for each pound load.

Figure 4 Air Bearing Stiffness

Compensation provides a way to control the flow of air into the air gap, and is the true key to tuning air perfect stiffness for a given application. The objective of compensation is to create a restriction of the airflow into the gap, before the restriction of the gap itself. Almost by definition, the air gap must act as a restrictor otherwise there would not exist localized pressure underneath the bearing and it would instead equalize with the ambient pressure.

But how can a positive pressure reservoir created by a restricted airflow provide stiffness? Consider the case of the orifice operating at 60 psi (a standard air bearing input pressure). At this input pressure the volumetric flow into the air gap under a 150 pound loading at a 300 micro inch fly height is equivalent to the flow out of the gap. A 2.5 inch diameter bearing has nearly 5 square inches of surface area, and so the average pressure across the face of the bearing is 30 psi. Now let us imagine the load is increased to 200 pounds. Referring back to Figure 4, we see that the average pressure increases to 40psi and compresses the air gap to 200 microinches, following the exponential stiffness curve. The squeeze film effect kicks in, reducing the air gap, increasing restriction, reducing the air gap, increasing restriction, reducing flow and resulting in higher stiffness. The reserve pressure being held back by the bearing now allows for higher pressure in the gap, creating a restorative reaction force which provides the air bearing with stiffness. In Figure 5, shown above, we see that compensation sacrifices raw load bearing capability for the benefit of providing stiffness and stability. Even without compensation, the maximum theoretical load

Last update: 2023-06-07

capacity of air bearing cannot be calculated directly from surface area and input pressure. A quick rule of thumb for air bearings is:

Surface Area x Input Pressure = Grounding Force

Surface Area X Input Pressure X efficiency = Load Capacity

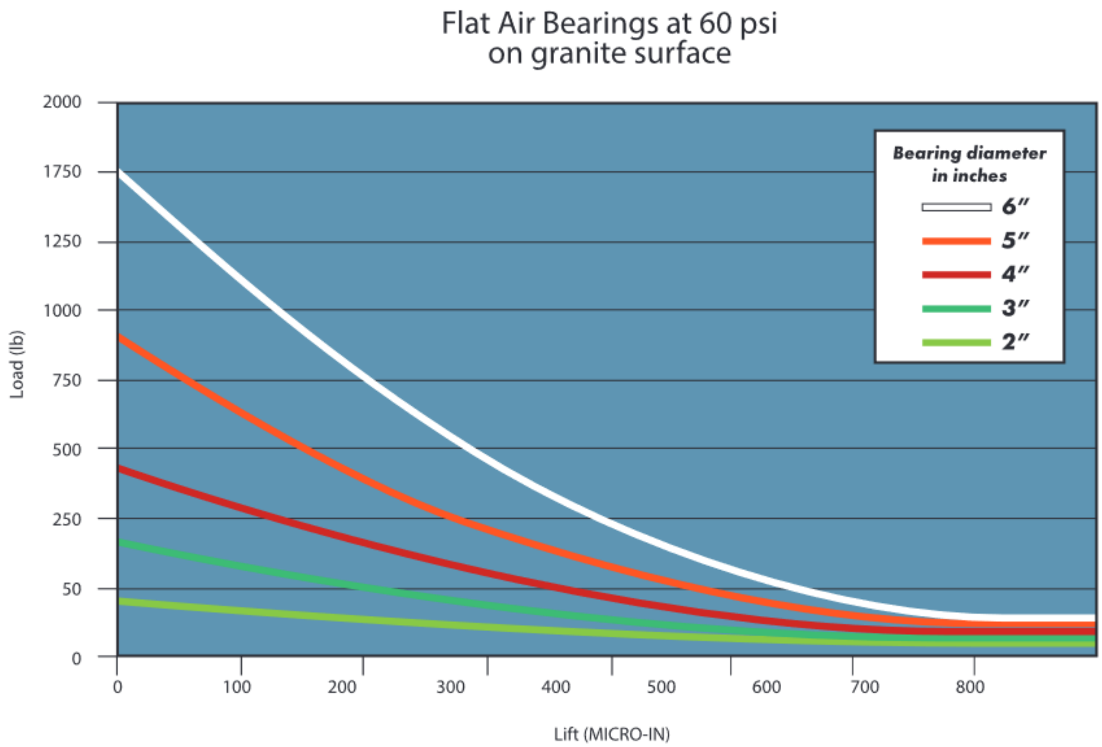


Figure 5 Lift-Load Curves

Air bearings do not carry their full theoretical load due to leakage around the bearing edges. This prevents pressure from being perfectly equal, and means a bearing loaded at its theoretical maximum would ground itself. As air issues from an orifice it expands through the gap, traveling towards the edges and giving rise to pressure gradients which can be mapped as pressure profiles, as shown below in Figure 7. These pressure profiles are a direct result of the amount and location of orifices and grooves, with porous media based systems providing the most even pressure distribution under the bearing. When compensation is used to increase bearing stiffness, the average pressure under the bearing is usually about 50% of the input supply pressure. Air bearings can therefore be considered 50% efficient with respect to input pressure, although this rule of thumb is modified by the size and shape of the bearing. Bearings which have a higher percentage of their area near the edge, like smaller or narrower bearings will have lower efficiencies, while larger bearings will have higher efficiencies. This is one of the reasons why smaller bearings are more challenging to produce. Although air bearings have a limited load capacity compared to rolling bearings, and even with a ceiling on input pressure, air bearings can provide the same load per unit area as traditional plain bearings for machine tools, and with their highly modular nature can support even heavier equipment

Last update: 2023-06-07

4 Types of Air Bearings Technology

There are two basic types of precision air bearings aerodynamic bearings and aerostatic bearings:

4.1 Aerodynamic Bearings:

Aerodynamic bearings rely on relative motion between the bearing surface and usually a series of spiral grooves to draw air into the bearing lands, creating pressure and a fluid film layer between the

two surfaces. This bearing action is similar to hydroplaning a vehicle at high speeds. At normal speeds, a tire would cut through the water, but at higher speeds, your vehicle hydroplanes. In the same way, aerodynamic bearings require relative motion of a sufficient magnitude to generate their fluid film layer. During start up and shut down, or “lift off” and “touch down” for machines operating off these types of bearings, the inner and outer diameters of the bearings will contact each other, leading to sliding friction and wear on the bearings. These bearings are often referred to as foil bearings or self-acting bearings

4.2 Aerostatic Bearings:

Unlike aerodynamic bearings, aerostatic bearings operate off an external, pressurized air source. This air pressure is introduced either by a series of holes, grooves and steps, or via porous compensation techniques. Because aerostatic bearings operate off an pressurized air source, they maintain their air gap whether the bearing is at rest or in motion relative to its guide surface.

4.3 Orifice and Porous Media Technology

Air bearings generally fall into one of two categories: orifice or porous media bearings. In orifice bearings, the pressurized air is supplied to the bearing surface through a small number of precisely sized holes, similar to the surface of an air hockey table, but with the holes in the puck. Porous media bearings operate quite differently, in that the air is supplied through the entire surface of the bearing (Figure 6). The porous material controls and restricts the airflow in the same way an orifice bearing would if it had millions of miniature holes across its surface.

The two classifications of air bearings also correspond to the two techniques for achieving the air bearing compensation effect. Orifice compensation has traditionally been the most widely used technique, but porous surface compensation has been established as the method of choice owing to its many advantages and increasing ease of availability.

In traditional orifice compensation bearings, the precisely sized orifices are strategically placed on the bearing, and are often combined with grooves to distribute the pressurized air as evenly as possible across the bearing face. However, should the bearing face become scratched across a groove or near an orifice, the volume of air which escapes via the scratch in the surface may be more than the orifice can supply, causing a bearing crash even at normal air supply pressure. Instead of the small number of orifices employed by conventional bearings, porous media air bearings control the airflow across the entire bearing surface through millions and millions of sub-micron holes in the porous material. Due to the porous nature, even if some of the holes become clogged or damaged, the air will continue to be supplied through the majority of the bearing face, maintaining fly height even after being severely scratched.

Figure 6 Porous Media

Last update: 2023-06-07

Even under normal circumstances, the air in an orifice air bearing is liable to lose pressure and generate pressure gradients in the air gap as one side dips, creating higher pressure and leading to a rise in the other side. The rising side will then drop down, perpetuating this behaviour in what's known as the pneumatic hammer effect, which can easily lead to damaging resonance behaviour and pressure related bearing collapse.

Porous media has been found to be one of the best materials for mitigating this behaviour, producing an ideal supply of uniform air pressure across the face of the bearing (Figure 7), all while automatically restricting and damping the air flow at the same time. Owing to the combination of the squeeze film effect and uniform air flow, as one side of a porous media air bearing is depressed, stiffness increases and it resists off axis motion, desiring to return itself to a stable equilibrium state.

The carbon surface, being lubricious, also provides greater protection for your system in the event of an air supply failure. Carbon is softer and more compressible than the steel or granite which often comprises guideway surfaces, and so in the event of a crash, the bearing surface will absorb kinetic energy, protecting the guideway and still retaining functionality, even allowing for bearings to be moved without an air supply.

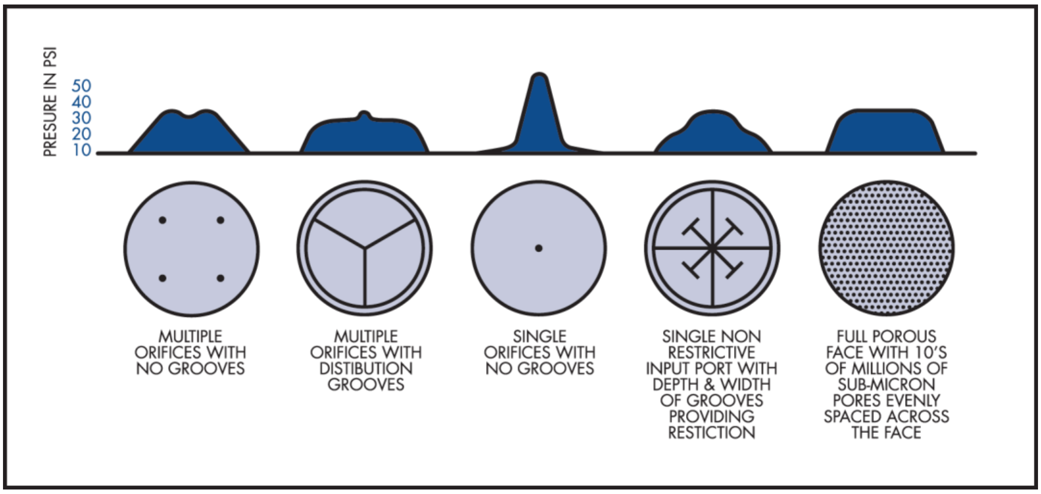
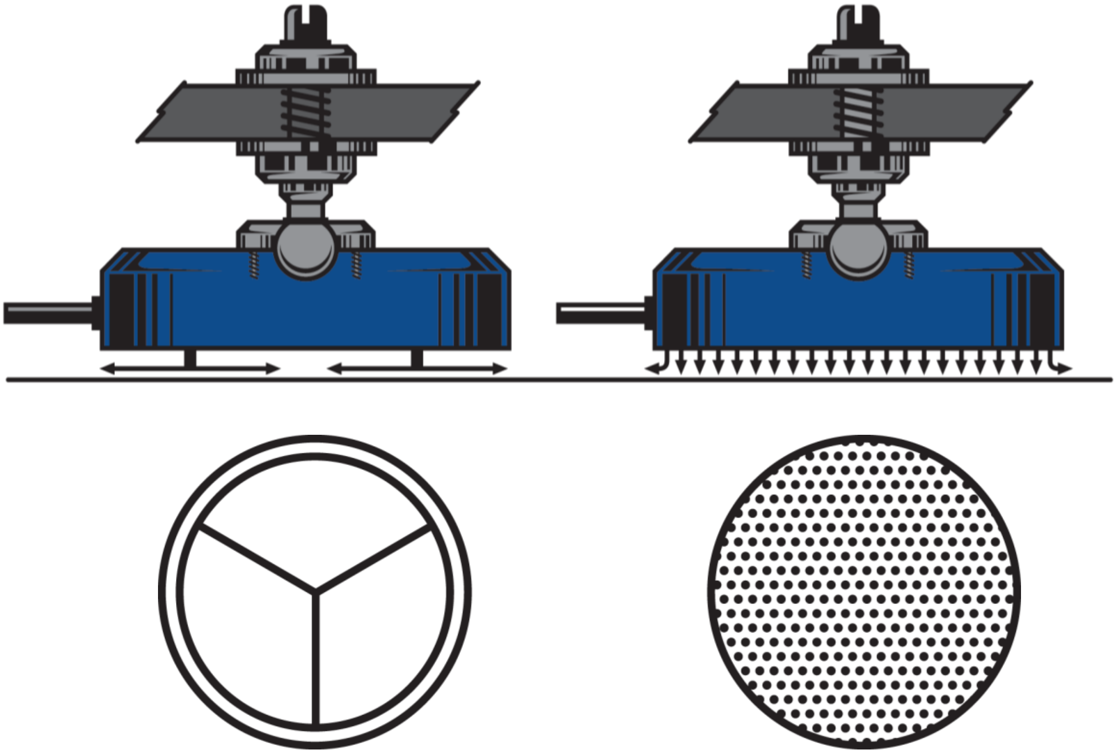


Figure 7 Air Bearing Pressure Profiles

Last update: 2023-06-07

4.4 Lift-off and Collapse

When grounded, flat orifice bearings only have the area of the orifice and the air distribution grooves available to provide initial lift-off force. This significantly limits the ability to preload orifice type air bearings, since the preload force often surpasses the initial lift-off capability of the bearing. Because porous media air bearings supply air pressure across the entire face of the bearing (whether flying or grounded) they do not suffer this problem, and may be preloaded prior to use.



When grounded, only the area of the orifice and grooves contribute to lifting force. A gap is necessary to create flow to distribute pressure.

When grounded, millions of sub-micron holes across the face make the whole face contribute to lifting force without gap or flow.

Figure 8 Orifice vs. Porous Media

Last update: 2023-06-07

4.5 Pitch Moment Stiffness

It is worth noting how the continuous lift capability of porous media air bearings distinguish them from their orifice bearing counterparts when discussing the pitch moment stiffness of an individual bearing. Since orifice bearings are dependent on flow across the face of the bearing, an angular change in the gap e.g. when one side rises and the other dips, will create an unstable situation. In this scenario, the available flow will rapidly lose pressure, following the path of least resistance out from under the bearing (the large gap) and away from the area which most needs pressure to stabilize it (the small gap). This in turn may cause the large side to collapse and the small size to rise, once again leading to the pneumatic hammer effect discussed earlier. In this same situation, a porous media air bearing still has pressure issuing from across the entirety of its bearing face, including the small gap side. This functionality is what provides porous media with higher tilt moment capacity, and thus stability.

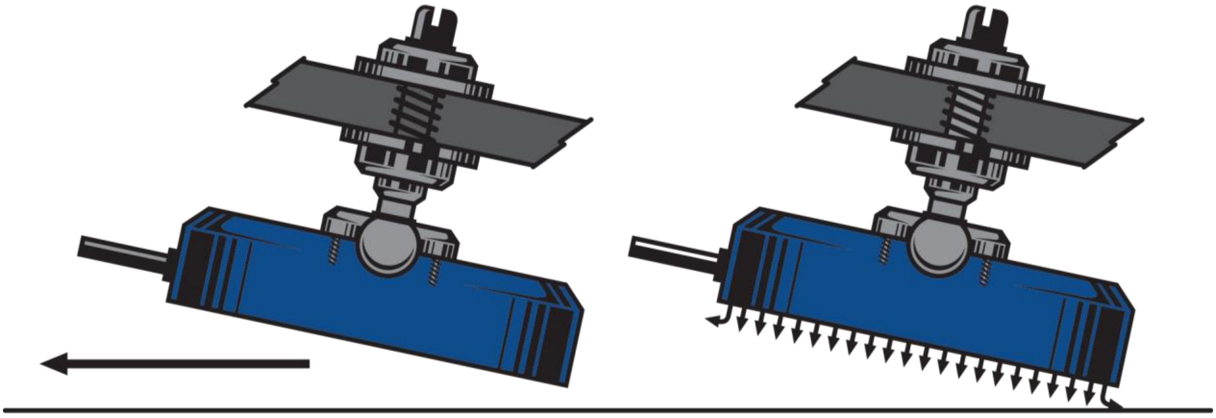


Figure 9 Pitch Moment Stiffness

Last update: 2023-06-07

5 Air Bearing Products

Air bearings are available in one of 5 broad categories, with more specialized varieties available for viewing on our website. Complete details on each type of air bearing product, including selection, mounting, configurations and handling are covered in the later sections of this applications guide.

Flat Air Bearings

Flat Bearings may be round or rectangular, and are typically mounted using a single threaded ball screw, mounted in the geometric center of the bearing. For added compliance, they may also be bonded in place using a patented vacuum replication process.

Air Bushings

Air bushings offer the least expensive method of utilizing air bearings technology. They are designed to fit standard size shafts, and can often be used as a direct replacement for existing bushings.

Vacuum Preload Air Bearings (VPL's)

Vacuum Preloaded Bearings, or VPLs, are similar to air bearings, but they utilize a vacuum chamber in the center of the bearing land, preloading the bearing against the guide surface.

Air Bearing Slides

Air bearing slides are complete slide assemblies which use opposing flat pad air bearings integrated into a compact package.

Radial Air Bearings

Radial bearings are ideal for very large rotary bearing applications and provide you with all the benefits of air bearings: no friction, no wear, no lubrication and no noise.

Last update: 2023-06-07

6 Air Bearing Applications

IBS Air Bearings are used in a variety of applications including: Coordinate Measuring Machines, Precision Machine Tools, Semiconductor Wafer Manufacturing, Medical Machines, Optical Lens Manufacturing, Digital Printers, Lithography, Precision Gauging, Diamond Turning Machines, Materials Testing Machines, Crystal Pulling, Rotary Tables and Friction Testing. IBS Air Bearings offer distinct advantages for different industries and applications, as outlined below:

6.1 Machines for the Image Setting Industry

This market encompasses machines for computer-to-plate (CTO) and high resolution scanning in the pre-press industry. These machines employ high speed, spinning optics traveling down the center of an internal drum. A laser beam is reflected off the optics and directed to the internal diameter of the drum, and air bearings are utilized in order to maintain a true axis of rotation and translate the spindle down the center of the guide. The Abbe principle states that pitch and yaw errors are magnified by the distance from the optic to the internal diameter of the drum, and using air bearings to minimize these errors results in fewer banding artefacts in the image.

6.2 Coordinate Measuring Machines

Most coordinate measuring machines (CMM's) are built with air bearings to allow for infinite resolution of motion. Because air bearings float on a pressurized film of air, there is no physical contact with the guide surface, and thus provides the system with a greater accuracy of measurement. The only source of friction comes from fluid shear in the air film itself. Additionally, the static and dynamic coefficients of friction are identical, eliminating the stick slip effect. This minimizes lost motion and reversal error in the triggering and positioning of the measurement probe, and since air bearings don't suffer from hysteresis error, they provide for truly repeatable motion, allowing for more effective error correction. Mechanically speaking, all this adds up to highly accurate, infinite resolution motion, subtracting one more confounding factor from the control engineer's list of variables to account for in the measurement problem solving process.

6.3 Testing Equipment

Many tensile and friction testing machines can be unduly influenced by the friction inherent to the rolling element bearings they operate off of. Wear in the bearings can also result in inconsistencies with testing procedures, further compounding the issue of accurate testing. To remove this issue, many of the most accurate friction testing machines utilize air bearings to eliminate mechanical contact friction. Many tensile testing machines require very precise force control, and eliminating friction further increases the resolution of force gauges and associated instrumentation. Fatigue testing (another type of oscillating test equipment) will often cause fretting, a kind of wear induced by repeated sliding contact on their rolling element bearings. Due to their non-contact nature, air bearings are insensitive to the high frequency of vibration which can occur in short travel applications, and display no greater wear in these types of applications

6.4 High Speed Equipment

Today's machines are being designed with elements which may perform upwards of a billion cycles a year. It is simply impractical to attempt accelerated life cycle testing on components like this, so another approach is needed to tackle the problem of high cycle fatigue. In this instance we can sidestep the problem entirely by switching from a roller bearing based system to one built on porous media, removing all wear in the process. For air bearings, travel and speed don't affect wear, only erosion from fluid friction does, so the only determining factor for air bearing erosion, and thus operational lifespan, is the amount of particulates in the bearing's air supply. Even assuming dirty

Last update: 2023-06-07

air is supplied to an air bearing, once the air has passed through the requisite filters, the calculated life of an air bearing is on the order of centuries, regardless of whether its stationary or performing billions of cycles a year. Since the dynamic coefficient of friction is correlated with speed, air bearings will begin to generate some amount of heat once they move above 100 feet per second. This can affect confined, rotating applications, though it should be noted that any heat produced is substantially less than contact bearings or oil lubricant based systems.

6.5 High Precision Machine Tools

Many of the most accurate machine tools in the world are built on porous media technology. The zero static coefficient of friction allows for unmatched performance during stage reversal in contouring operations. Highly accurate velocity control and elimination of perturbation in the stage movement allow for lathe turning of optical quality finishing, measured on the order of angstroms. Any manufacturing errors in product geometry which might be attributed to air bearings are on the order of several millionths of an inch.

6.6 Linear Stages

Air bearings, especially porous media air bearings are often incorporated into high speed, high resolution linear stages, in order to take advantage of the ultra-high speeds and movement resolution they offer. IBS modular air bearings allow ultra-precision, frictionless stages to be designed and built with standard, off the shelf components that are inexpensive and easy to retrofit.

6.7 Original Equipment Manufacturers

Air bearings are often found throughout Original Equipment Manufacturers (OEM's) precision machine applications. OEM's can either incorporate complete linear stages into their machines, or integrate their own stages using modular air bearing products.

6.8 Custom Projects and Test Rigs

If you thought air bearing technology was unattainable or beyond the scope of your one-time, custom project, think again. IBS is the premier supplier of standard, modular air bearing products which can be easily integrated into your custom machine, test rig or gaging application, With a wide selection of flat air bearings, air bushings, vacuum preloaded air bearings and air bearing slides in stock, the benefits of porous media technology are available to those with even the smallest project. The frictionless properties of air bearings provide for finer resolution of motion and allow for significantly lower forces than can be achieved with comparable rolling element bearings.

Do you like the benefits of porous media but don't see a product that meets your needs? IBS is also proud to offer turnkey engineering services, with in-house design and manufacturing of products custom built for your exact need. Please contact our application engineers today to discuss your intended use and find out what IBS can do for you!

Last update: 2023-06-07

PART II: CHOOSING AIR BEARINGS

7 Selecting the Right Air Bearing Product for your Application

The charts on the following two pages can be used to select which air bearing product is best suited for your application, and what effect the operating environment may have on air bearing performance.

Air Bearing Product Selection Chart

	Flat Pads	Bushings	VPL's	Stages
Cost	This is the most common type of air bearing stage in use. Pads are inexpensive. Stage structures are inexpensive. Guide ways are the more expensive component. The number of bearings can add up in a large or complicated application	This is the least expensive air bearing system. Round shafting is readily available. Only three bushings are required to constrain a stage to a single axis of motion.	Using VPLs on a single plane can provide X and Y motion, saving costs. However, VPLs are more expensive then flat pads as they are more complicated and larger. VPLs are often flexure- mounted which can also add to costs. VPLs may be bonded into place with a patented process to reduce mounting costs.	Air stages have air bearings integrated into them and fit to a guide way. This minimizes assembly, inventory, and purchase part lists for the customer, but will most often be the most expensive.
Assembly	Easiest assembly. Low cost mounting components. Flexibility in alignments from threaded studs.	Easy assembly. O-rings provide self-alignment. Mounting components are easily sourced by the customer or can be purchased from IBS Precision Engineer.	VPL systems require more assembly care. Most flexure designs are somewhat fragile. Patented vacuum replication process can be employed (with license agreement) for robust and inexpensive mounting.	No customer assembly required
Precision	The straightness of motion will be dependent on the accuracy of the guide ways used. When pre-loaded by an opposing pad the stage will be over-constrained. In some cases, errors in the guide may be average	Round way stages can achieve high accuracies especially when strokes are limited to less than 6". Most bushing stages are employed where smoothness, speed, or low friction are required.	Because VPLs can be arranged kinematically correct, the highest precision is possible. Of course, other precision engineering principals will also need to be adhered to in order to achieve this high precision.	Because stages can often have more air bearing surface area and shorter distances between pay load and guide, they will have higher stiffness and less angular errors caused by off drive axis masses.

Last update: 2023-06-07

Stiffness	Preloaded flat pads have high stiffness. In most cases bending or diaphragm effects of the structure result in lower structure stiffness than in air films.	Since bushings guide on end-supported shafts, bending of the shaft is usually the limiting factor in system stiffness. The O-ring mounting can also limit stiffness. A simple potting procedure can hard fix this compliance. Stiff stages can be constructed with short strokes. See bushing section for more detail on how gaps affect performance.	VPLs have variable stiffness. System stiffness is often limited by the mounting flexure. Our standard VPLs are best used in lightly loaded, low acceleration, ultra-high precision applications where their exact constraint is used to advantage. More robust systems with higher load capacities and stiffness can be constructed using large custom VPLs and our replication process.	IBS air stages built with the patented replication process offer the highest stiffness for a given space.
Load Capacity	Flat bearings have the highest load capacity. Custom bearings can carry over 10,000 lbs each.	Air bushings have limited load capacity. Being O-ring mounted it is possible to gang them together to increase load capacity.	Flexure mounted modular VPLs have very limited load capacity. Larger, bonded VPLs can have much higher load capacities.	Stages can have high load capacity.
Plumbing	Plumbing is simple. One air line goes to a manifold on each axis, with bearings from that axis fed from the manifold.	As air bushing stages can be made with fewer bearings, plumbing is often simpler	Additional air line required for vacuum. Vacuum air line should be larger diameter for good conductance.	Air Stages are the simplest to plumb. They require only one air pressure line.

Last update: 2023-06-07

Effect of Environment on Air Bearing Performance	
Environment	**Effect on Air Bearing Performance**
Dust	Very resistant to dry dust. Will clear a path on a dusty surface. Care should be taken not to let dust build up at ends of travel or it will tend to pack clearance areas full. Consider angled surfaces to reduce this effect.
Oil	Oil dripping on the guide way must be avoided! Oil will fill the air gap and create drag. Disassembly, cleaning and possible replacement of bearings may be required (see cleaning issues).
Water	Water dripping on guide way must avoided! Water will fill the air gap and create drag. Drying the guide way and supplying clean, dry air to the bearings will restore original performance. Be wary of corrosion or caustic reactions of the guides to the water.
Temperature	Stock Air bearings are designed to operate at room temperature. A variance of +/-30°F is acceptable in almost all applications. Larger bearings will be affected more by temperature differences. Pay close attention to thermal effects on your structures

Last update: 2023-06-07

PART III: Designing with Air Bearings

8 Air Bearing Guides

Air bearings can operate on different types of guide materials. Common guide surfaces include granite, hard coated aluminium, ceramics, glass, stainless steel and chromed steel.

8.1 Guide Surface Considerations

Surface finish, local flatness and holes in the guide surface should be taken into consideration. Call us to discuss your specific application requirements, and guide surface parameters which you believe could affect performance.

8.2 Surface Finish

IBS Precision Engineering recommends a surface finish of 16RMS (micro-inch)or better. Although rougher surfaces may be adequate, we ask that you discuss your specific application with us before employing air bearings in such a situation. For porous media air bearings, the surface finish must be considered as being part of the gap, so surface finishing becomes more crucial as you design for smaller gaps. Additionally, damage is more likely to occur to the bearing face during an unexpected touchdown, should your guide surface have a rougher surface finish.

8.3 Local Flatness

Local flatness, which we define as the flatness under the bearing at any one time, should be less than 50% of the designed air gap. This is a worst case scenario, and in reality it is relatively easy to stay below 10% of the air gap

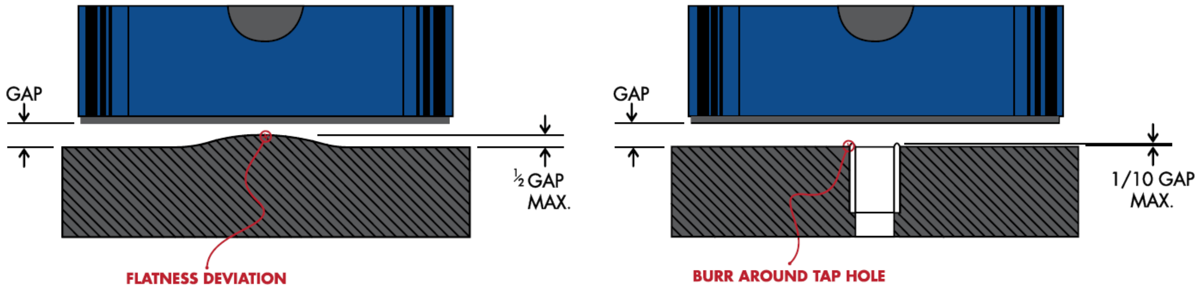


Figure 10 Surface Flatness

8.4 Holes in the Guide

With respect to holes in the guide surface, it should be remembered that air bearings work off of the pressure produced against an opposing surface, and thus air bearings do not work when flying over holes. However it's actually these types of applications where porous media air bearings really stand out. Admittedly we pay a small price in that a lower lifting capacity must be accepted, depending on the sizing and frequency of the holes in the guide way surface. Exactly how much lower? For example, an 80mm bearing flying over an optical table with 1/4-20 threaded holes on one inch centers will have about 50% of its normally load capacity at 10 microns of fly height. The higher the air pressure in the gap, the higher the efficiency loss from the holes will be.

Last update: 2023-06-07

8.5 Seams in the Guide Way

Seams in the guideway should be avoided. With an air gap of 5 microns, a step in a seam of 10 mm is analogous to hitting a wall, and should be avoided for the benefit of bearing life.

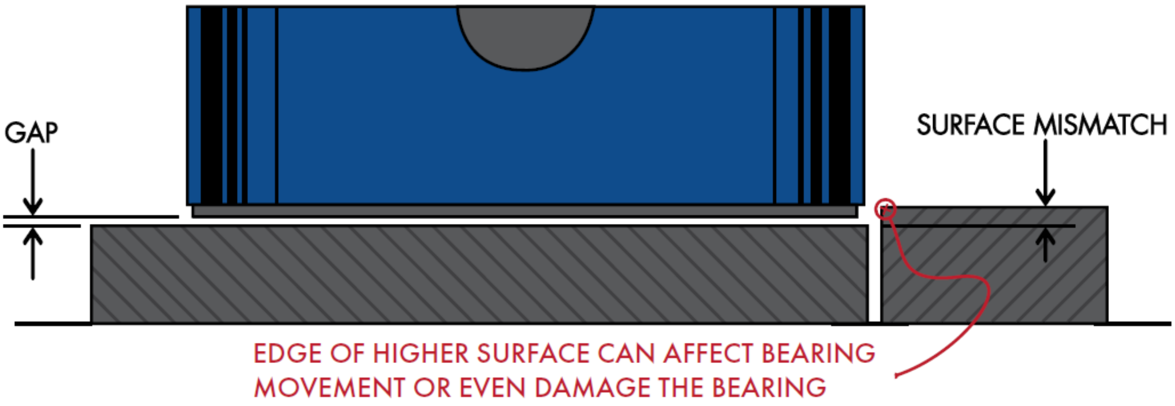


Figure 11 Seams in the guide way

9 Stiffness and preload

Stiffness is an important factor to consider when designing any precision motion system, since bearing stiffness will contribute substantially to overall system performance. The higher the stiffness, the less compliance there will be when loads are applied, and the more accurate the overall structure will be. Preloading provides one method for increasing stiffness and accuracy, and is applicable across all types of porous media air bearing

Preloading contact bearings follows the rules of Hertzian contact stresses. These contact stresses are localized stresses which develop as two curved surfaces coming into contact, deforming slightly under the imposed loads. As a ball bearing is pressed against its race under higher preloads, the point or line of contact becomes larger, due to the deformation of the contact surfaces. A larger contact surface will lead to greater stiffness, and for contact bearings, must be weighed against the higher friction and reduced life of the bearing from contact stresses. Preloading air bearings follows the rules of fluid dynamics and more specifically, the squeeze film effect of compressible fluids. Because air is a compressible fluid, it possesses its own spring rate, or stiffness. Higher pressures effectively act as a preload on the “air spring”, and if we think of the air column as a spring of arbitrary height, compressing or shortening the spring will increase its stiffness as the air attempts to “push back”. Stiffness in an air bearing system is a product of pressure in the air gap, thickness of the air gap and the projected surface area of the bearing. Intuitively, it may be difficult to conceptualize how an air bearing could have stiffness commensurate with a roller bearing, which is in physical contact with the guide surface, however it should be noted that a point or even a line has, theoretically, no area. Such minimal contact areas create very high local stresses, and so require hardened materials to avoid large deformations of the roller or race elements. In air bearings, the load is transmitted through an air gap projected over an area several orders of magnitude larger than rolling bearings. The wide air gap is what enables the squeeze film effect, providing the positive correlation between stiffness and damping which is entirely unique to air bearings, and which is highly advantageous to precision systems. Air bearings may be preloaded through numerous methods, including added mass, magnets, vacuum, or mounting two air bearings in opposition to each other in either side of a guide rail. Each of these techniques offer their own distinct benefits and drawbacks. Adding mass can often run counter to the requirements for high acceleration and short settling times we see from high speed machine tools. Magnetic preloading requires the guide surface to have metal under each axis and so metal strips would need to be inserted into a granite base, adding to the cost and complexity of the structure. Air bearings are most frequently preloaded through positioning them opposite each other, as shown in Figure 12. This requires a significant amount of space, two parallel surfaces and doubles the total mass of the bearing components. Vacuum preloading offers the most effective and elegant preloading solution of the available options, minimizing bearing mass and height, and is effective on both granite and metallic guide surfaces.

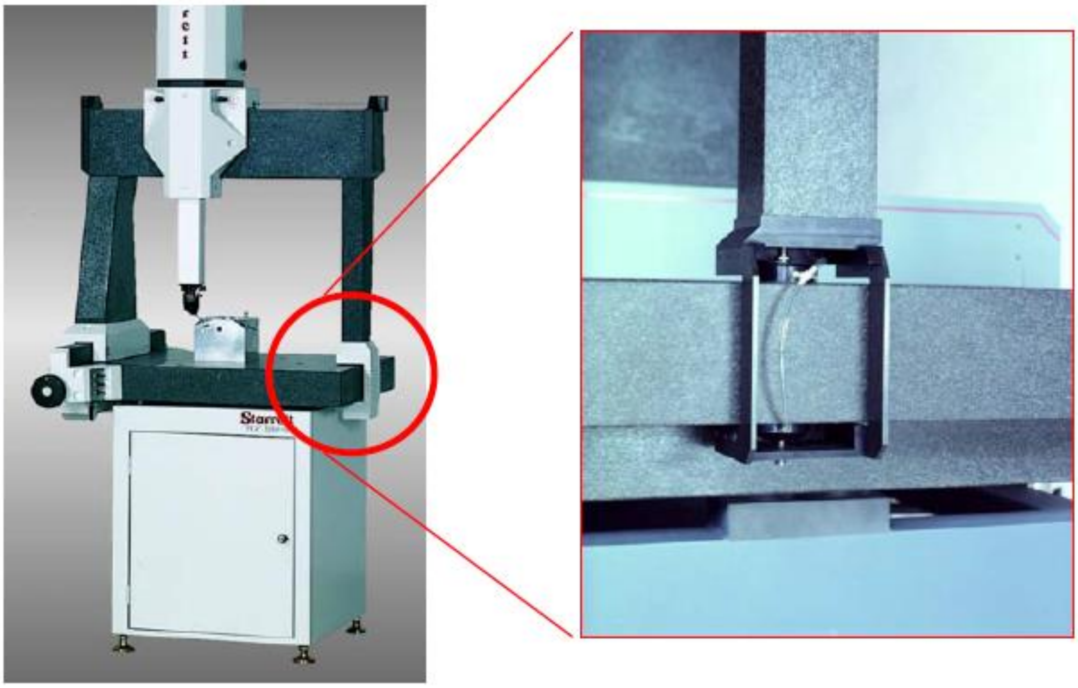


Figure 12 IBS Air Bearings on a Coordinate Measuring Machine

Last update: 2023-06-07

9.1 Preloading methods

1. Air bearings can be preloaded by adding mass; for example, moving a large object about on the surface of a precision granite plate or optical table. This is generally best accomplished by the use of a 3 bearing configuration, as 3 points describe a plane, and thus can be adjusted to remove motion in the Z axis when configured for XY motion. When supporting a known mass, the bearings should be sized so that the load each individual bearing carries will drive the air gap to the desired point on the lift load curve, and thus produce your desired stiffness. Sometimes stiffness isn’t a primary design consideration if there isn’t an anticipated change in loading, or there may be a desire to fly bearings over higher surfaces which aren’t perfectly flat. If we again consider the case of an aluminium optical table with quarter 20 holes on one inch centers, you may find localized high spots as a result of burrs on the hole edges, or resulting from other forms of machining imperfections. In this instance, we could select an oversized bearing which would result in a higher fly height and thus withstand greater abuse.

2. Air bearings can also be preloaded through vacuum. Air bearing lands or any inactive surface which has been finished at the same plane as the bearing face can be used as a vacuum seal. It is counterintuitive that an air gap which is pressurized with air can also be a seal for the vacuum, but it works very well. It is perhaps easier to conceptualize when we consider that a vacuum preloaded bearing may consume less than five cubic feet of air per hour, and only half of that will find its way into the vacuum chamber. Furthermore, this loss of air can be reduced through the use of ambient pressure groove between active bearing land areas, combined with seal lands, thus dramatically reducing even this small flow into the vacuum. The vacuum load is created in the center area where vacuum is drawn, using outside atmospheric pressure to press down on the bearing and create a preload force equal to the projected area of the vacuum pocket times the pressure differential. This pressure differential can easily be two thirds of a perfect vacuum or -10 PSIG. Vacuum preloading is advantageous since it creates a preloading force without adding mass. Vacuum preloading may also be accomplished over an XY plane. A vacuum preloaded air bearing with a projected area of 12 square inches can create over 800 pounds of preload force with a stiffness well over 2 million pounds per inch, all with only a single pound of payload. This technique is highly advantageous when high acceleration stages also require low settling times. By guiding XY motion off of a precision plane, the Abby errors, which define the magnification of angular distance over a distance, may be eliminated. This technique also eliminates tolerance build-ups from stacked linear axes, providing for exceptional flatness of motion.

3. Magnets, similar to vacuum, can also provide a preload force without adding much mass. Metal strips parallel to the guide surface can be used to provide an axis, but to preload along X and Y, the entire guide surface must be metal. Magnets are often used between two air bearings, mounted in a threaded holder which allows adjustment of the magnets to the metal strip. Adjusting this clearance between magnets allows for the preload force to be optimized.

4. Air bearings are most frequently preloaded by the use of another air bearing. The stiffness of air bearings is additive, and so the addition of a second air bearing can double the system stiffness along a given axis. For air bearing preloading, it is best to preload bearings directly opposite one another, using bearings of the same size and same force, in order to avoid structural distortions.

Last update: 2023-06-07

10 Loads acting on Air Bearing Systems

10.1 Gravity loading

Structural loading

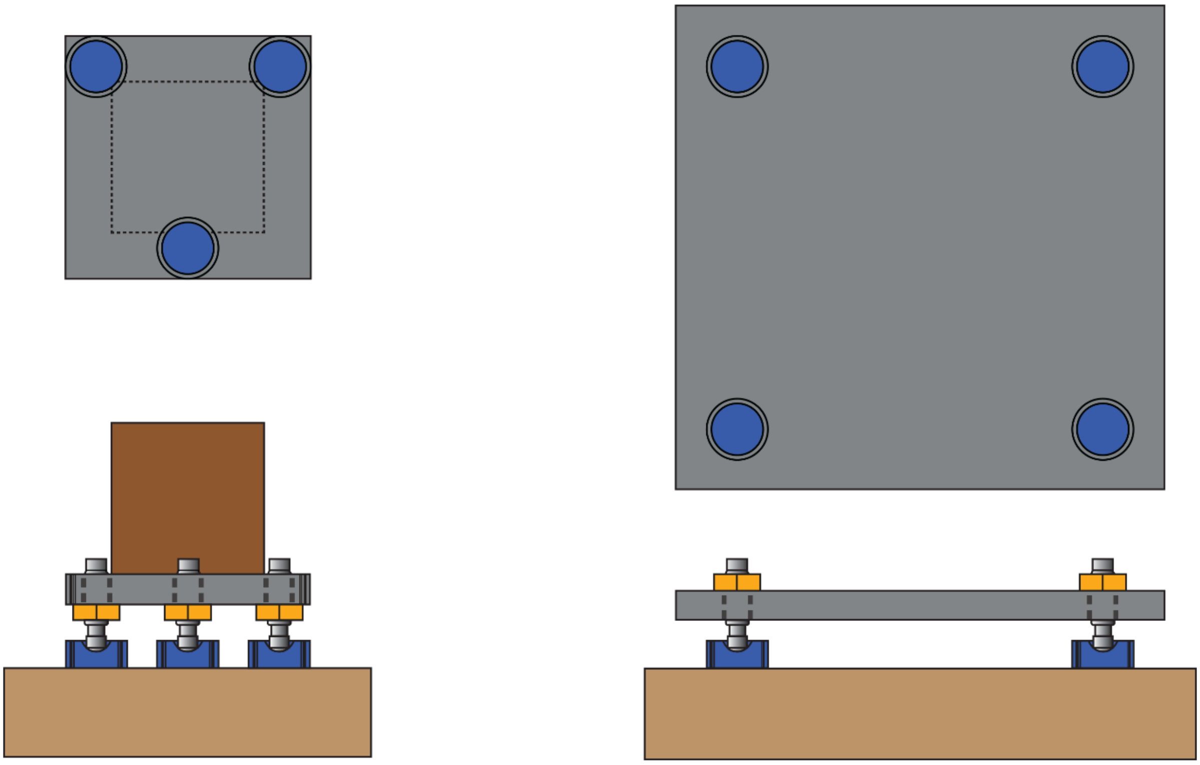


Figure 13 Supporting a load on a flat plate

When supporting a simple load on a flat surface, it is often best to use three bearings for a three-point, tripod stance. This avoids the four legged chair "rocking" problem, where one uneven contact point can unbalance the other three, whereas a triangle is always stable (see the section on kinematics). The three-legged stance is especially important if the structure being supported is very stiff (having a tall cross section), or if the guide surface is not very flat. If the structure being supported is not very stuff (say a plate with widely spaced bearings), a four-legged stance may be more stable, by virtue of a wider footprint. In this instance, the plate would be considered more elastic rather than as a purely rigid body

10.2 Payload Distribution and Mobility

Consider whether your load will be evenly distributed across the bearings. Will there be a change in payload, will the load change position as another axis stacked on top might? An appropriate rule of thumb is to size the bearings such that the maximum load the bearing will carry will not result in an air gap less than you are comfortable with (ideally 3 to 5 microns). This value can be determined from our provided lift load charts. Please note that for an added safety factor, larger bearings run at lower pressures can reduce airflow requirements and increase damping and stiffness when compared to a smaller bearing, sized at its margin of capability and run at a higher pressure.

Last update: 2023-06-07

10.3 Preloading with other Air Bearings

When preloading with other air bearings, the preload force you need should be considered when sizing the bearings. Preloading with air bearings is primarily employed to provide bidirectional load capacity, or to increase the air film stiffness. When the preloading forces are high relative to any anticipated changes in load, stiffness will also be high. In other words, larger bearings preloaded against each other will result in higher stiffness. This is a result of air bearing stiffness being additive, so two bearings opposing each other will have double the stiffness of just one bearing. For example, two bearings producing 500,000 pounds per inch stiffness each will produce a total one million pounds per inch stiffness. It should be noted however that for your calculations, the preload force must be subtracted from the load capacity of the bearings themselves.

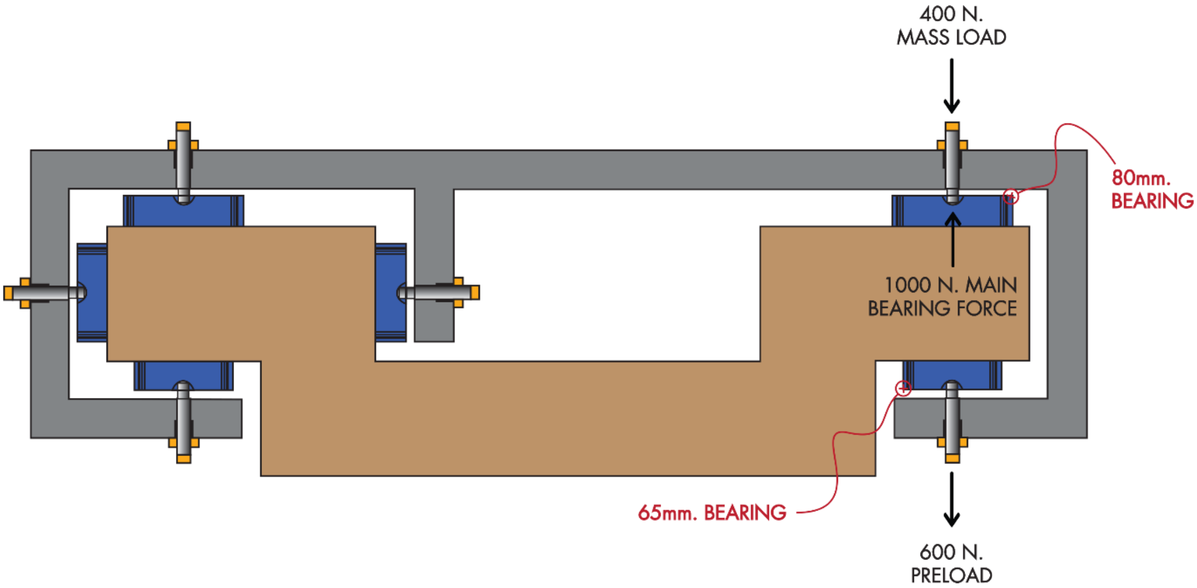


Figure 14 Preloading with other air bearings

Last update: 2023-06-07

10.4 Dynamic loading

When designing a high performance stage, i.e. one which requires high acceleration and fast settling times, it is critical to drive the stage along the assembly's center of mass. While this may not always be possible due to pre-existing design considerations, any mass off the drive axis will result in a force moment. This force moment will be imparted to and must be resisted by the bearings during acceleration and deceleration, and so these dynamic loads should be considered when sizing your bearings. The below models presumes no change in the air film stiffness and infinite stiffness of all structure

The below models presumes no change in the air film stiffness and infinite stiffness of all structures.

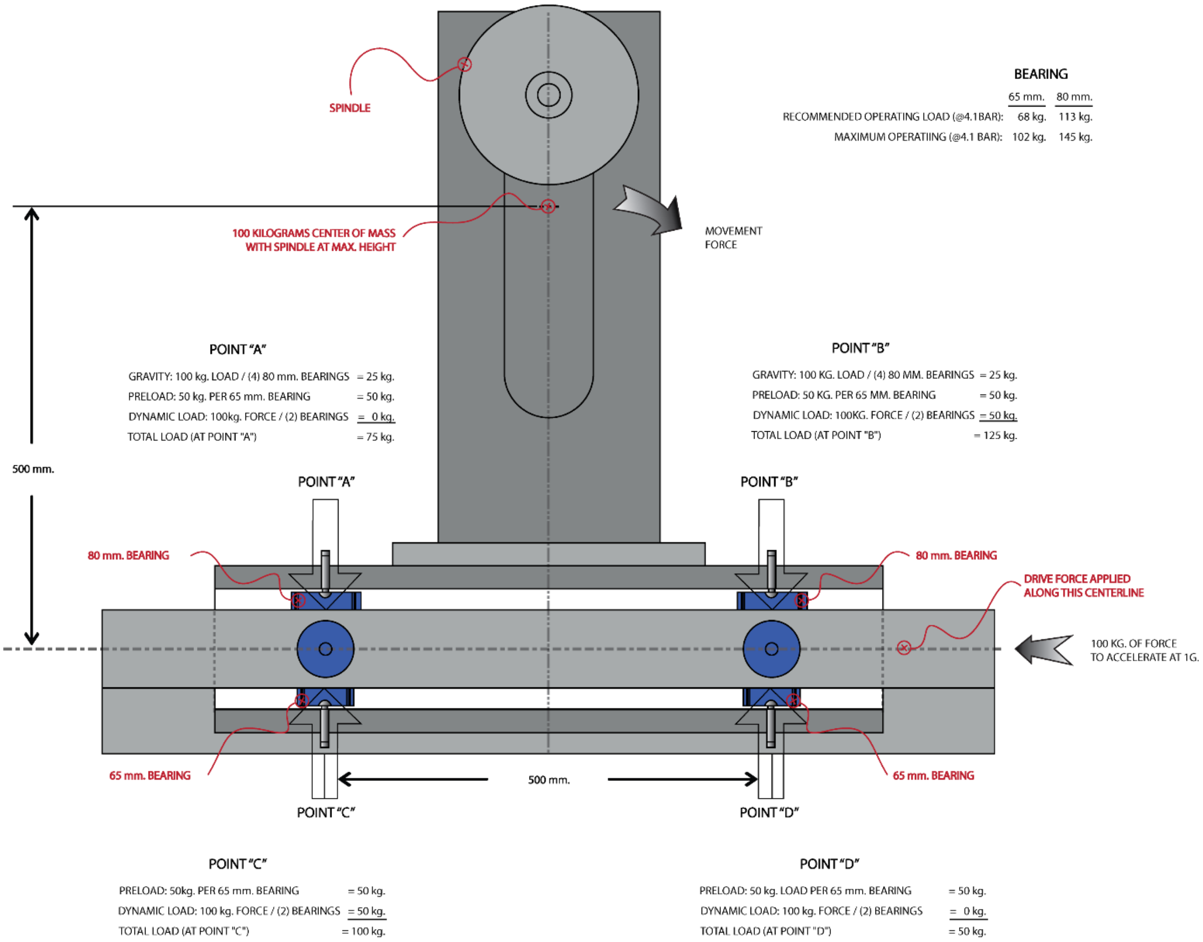


Figure 15 Dynamic Loading

Last update: 2023-06-07

Part IV: Setting up and using Air Bearings

11 Flat Bearings

11.1 Mounting and adjusting

What is the benefit to mounting flat pad air bearings with ball studs? When mounting air bearings, it is critical for the face of the bearing to be parallel it's running surface. Even a few microns worth of misalignment in parallelism across a 75mm air bearing would significantly degrade the bearing's performance. Because of the need for constant alignment with your running surface, it is difficult if not impractical to bolt bearings in place in a rigid fashion. A spherical socket and ball stud are much more effective and cost friendly than the precision match machining required to bolt the bearings in place, such that perfect parallelism is achieved. Additionally, threaded ball studs make alignment and preloading much easier, speeding up machine assembly, and their modular nature makes them easy to change or replace as needed.

Figure 16 Ball stud options for flat air bearings

IBS Precision Engineering offers two types of ball studs:

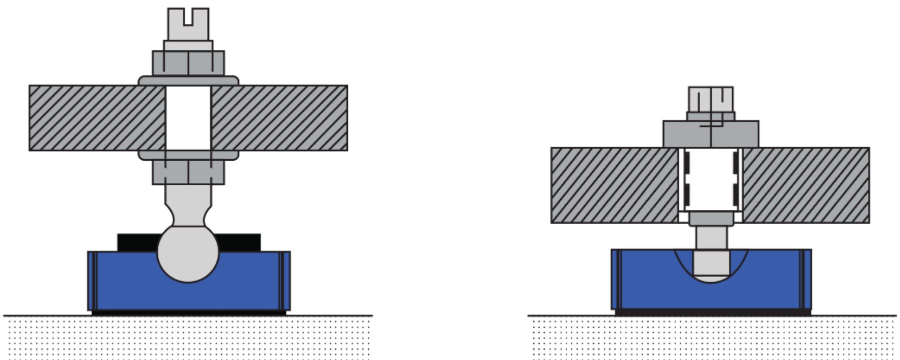


Figure 17 Round-End and Flat-End

Last update: 2023-06-07

IBS' metric bearings provide three threaded holes to accommodate a retaining clip to keep the bearing on its ball stud. The ball studs themselves are available with fine or medium pitch threading, and the studs come with two nuts and washers so it may not even be necessary to tap a hole in your existing structure. IBS provides complete drill, reamer and tap information on our website in order to help facilitate easier installation and adjustment of the bearings. The retainer clips are especially useful if the supporting structure may be picked up and moved, say to another test stand, or if the bearings face upwards towards a flat platen which may be placed upon them and removed with regularity. The retaining clips are also valuable in a setting where the bearings are used to guide a vertical ram, and you wish to lock the bearings in place while the ram is inserted. The diameter of the ball is larger than the threading diameter, so as to ensure it can screw in from one side only. Additionally, once the ball stud is in place, it is extremely difficult to screw the retaining clip on or off. This means the clip and bearing must be assembled on the ball stud prior to the balls stud's installation onto the structure, and more clearance between the back of the bearing and mounted structure should be allotted to accommodate the bull stud assembly. This style ball stud is available for both metric and imperial bearings, but threaded holes for the retaining clips are only available on metric bearings. Complete drawings of our studs, retainers and bearings are available on our website.

IBS insert Nut Housings are also extremely convenient to use. The Nut Housings consist of a brass insert, with fine threads to allow for preload and adjustment, and a coarse thread along the diameter which threads into the stud structure. Additionally, the brass insert itself features a set screw to lock the stud into adjustment once it's been dialled in. The stainless steel stud ends in a spherical end which is smaller than the thread diameter, making it possible to remove the stud from either end. The Nut Housings can also be adjusted via wrench flats, located just above the spherical end on the bearing side of the stud assembly. Minimal clearance is required between the back of the bearing and the structure, conserving space in your assembly. If you need to swap out bearings, they can be readily replaced by backing off the ball studs and slipping the bearing out. This style ball stud is available for both metric and imperial air bearings, with complete drawings available on our website.

11.2 Adjusting Main Bearings

The main load bearing pads are used to set the elevation and alignment of the state by adjusting the threaded mounting studs. With the air pressure turned off, adjust the elevation and angle as desired (note it may be necessary to hold the bearing in place with your fingers to keep it from rotating with the studs as you adjust them). If you are also using bearings to provide preload, turn the air pressure back on and adjust the two line side bearings for location and yaw alignment, and then tighten the preload bearings to eliminate any visible clearance.

Last update: 2023-06-07

11.3 Adjusting Preload Bearings

There are multiple methods for adjusting preload bearings. Here we describe four methods, including one which allows for physical checking of the air gap through the use of a precision metrology instrument.

1. Adjusting by drag: With operating pressure on, tighten the pre-load bearing until drag can be felt along the axis of motion, and then back off tension until you can no longer feel drag. Even with an 80 pitch screw, this can be a sensitive adjustment, and we advise using a long handle wrench for increased sensitivity. The stiffer the structure and the smaller the bearings, the more sensitive the adjustments will become.
2. Adjusting by Pressure: With full operating pressure supplied to all other bearings, supply two-thirds of the operating pressure to the preload bearing, tighten the bearing until it just begins to drag, and then supply full pressure to the bearing.
3. Adjusting by Flow: With a flow meter in the line supplying the bearing which is to be adjusted, measure the flow through the bearing with no load, and with the adjustment screw loose. Then, tighten the bearing until the flow is reduced to 60% of the original flow.

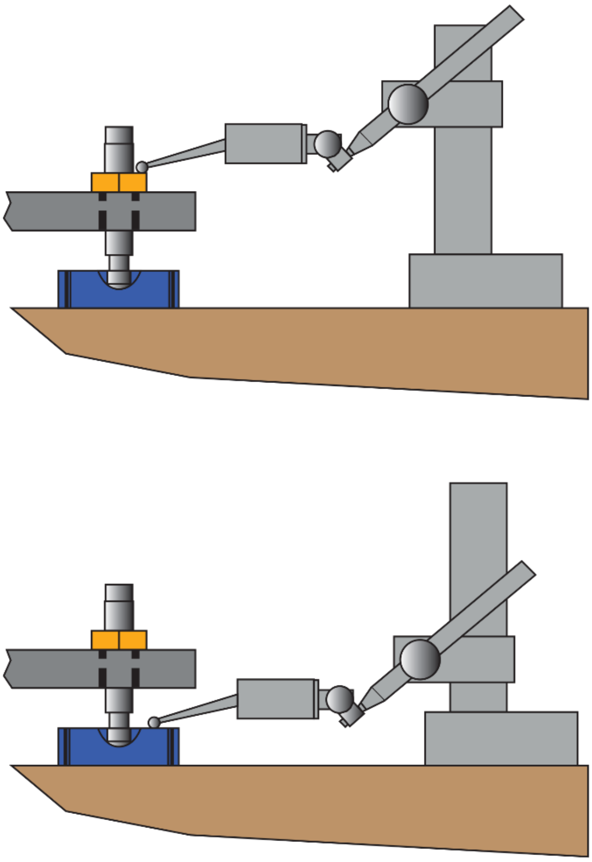


Figure 18 Adjusting using dial indicator

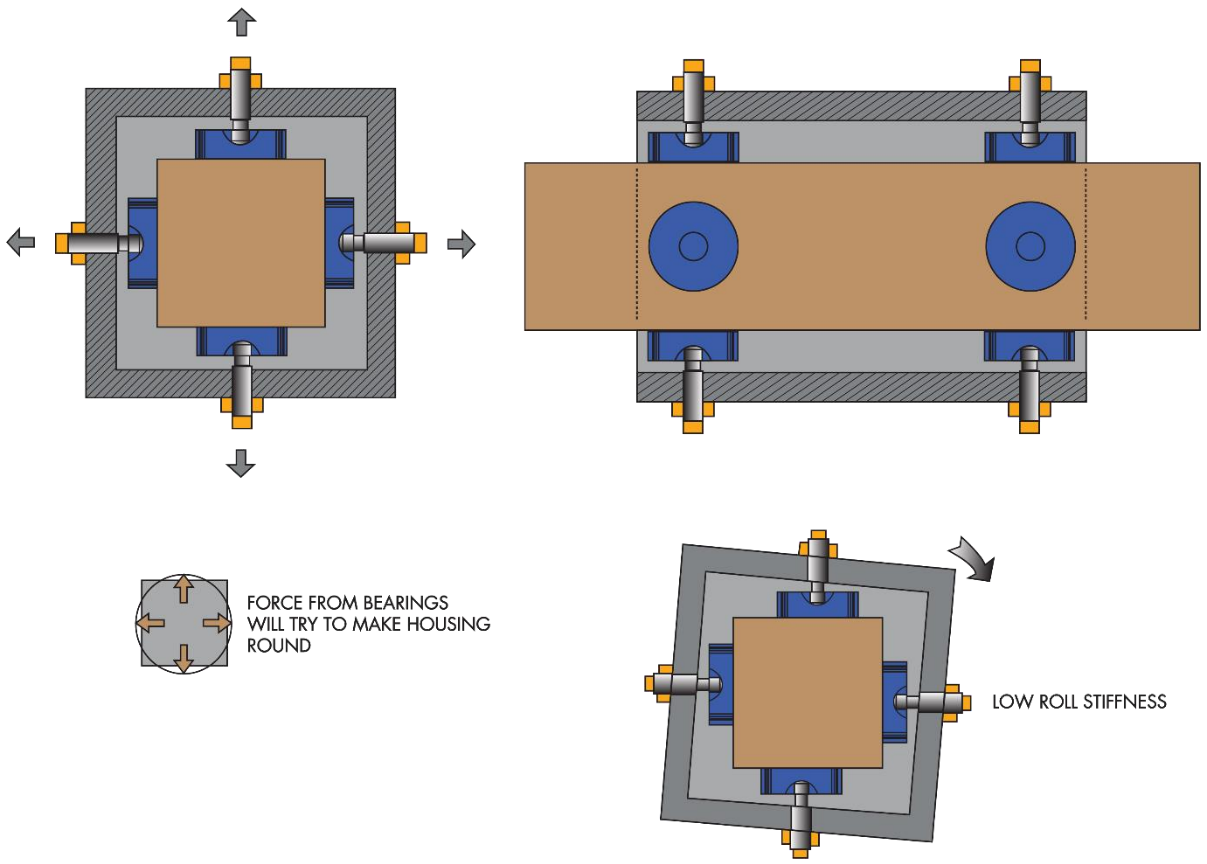
In the case of procedures 2 and 3 where pressure and flow are utilized to adjust the bearings, we recommend plumbing the bearings in parallel, using a stage mounted manifold with quick-disconnect fittings, which will greatly speed up the process. The fourth method of adjusting air bearings involves using an indicator to check the actual fly height of the bearings (see Figure 18). We recommend this procedure as an extra level of validation on the previous three methods and to help refine your procedures for the first few machines you adjust.

4. By Measuring Displacement: With the preload bearing tightened, position the indicator tip on the back of the bearings about 5mm (0.25 in) from the edge of the ball socket. With the air pressure turned off, zero the indicator, then turn the air pressure back on and read the indicator. Turn the air pressure back off and see if the reading returns to zero. If it does not return to zero, repeat the process until consistent readings are achieved. It is not unusual for technicians to overtighten the preload bearings (with pressure off) to help seat the ball studs in their sockets. This can result in more consistent readings and provide for a marginal gain in system stiffness. Finally, compare the displacement measurements to the design fly heights, and adjust the preload bearing accordingly.

Last update: 2023-06-07

11.4 Typical Configurations

The following pages show typical configurations of flat air bearings with brief descriptions of benefits and/or drawbacks.



This design suffers from low roll stiffness although it makes for easy alignments and setup.

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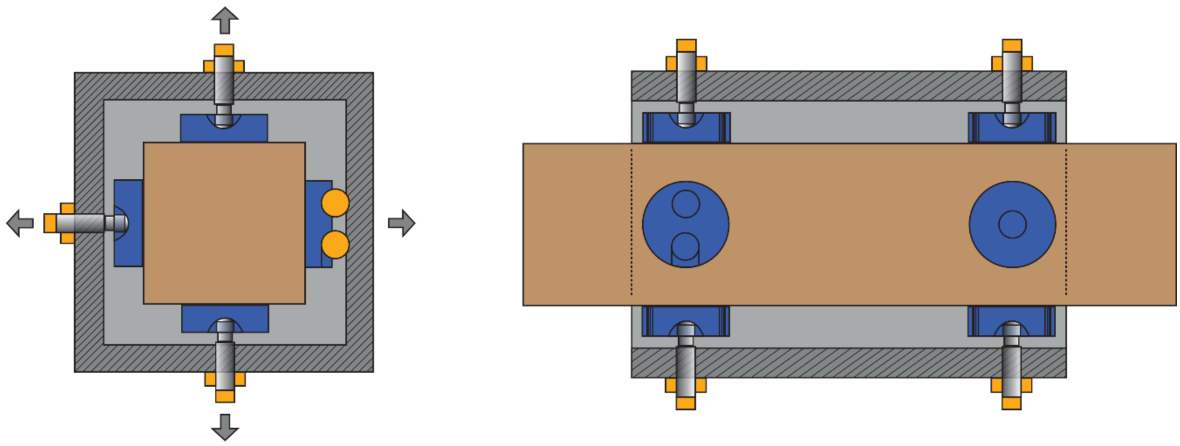
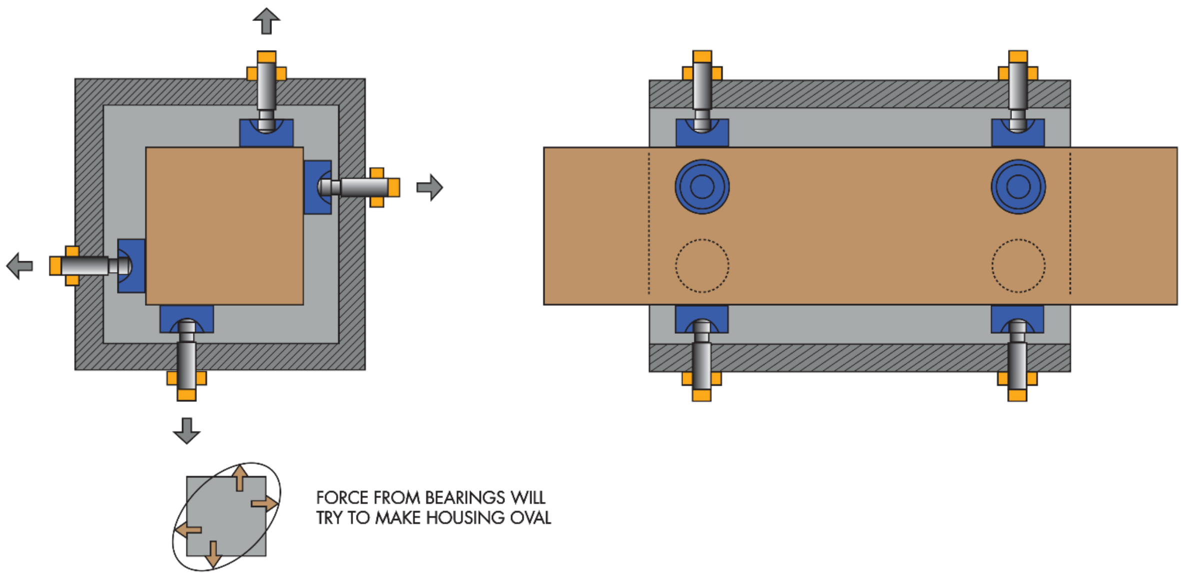
Using a second ball in a locating slot on one of the bearings constrains the roll about the axis. Stiffness and roll capacity is still limited to the pitch stiffness and roll capacity of a single bearing.



This design has higher roll stiffness. As the bearings are not directly across from each other it can be difficult to separate angular adjustments from roll adjustments.



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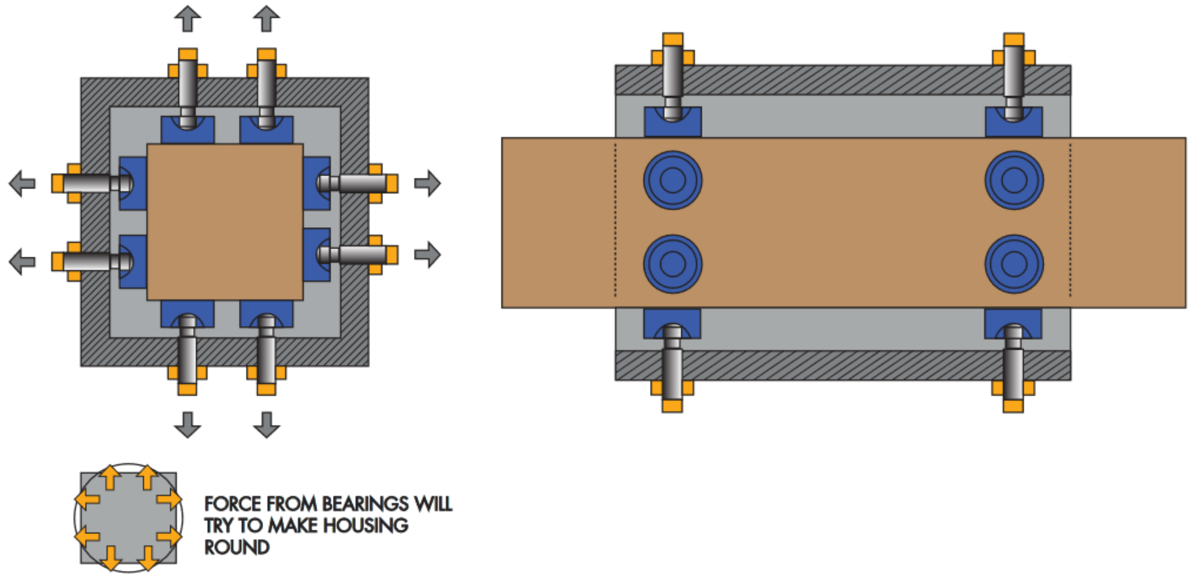
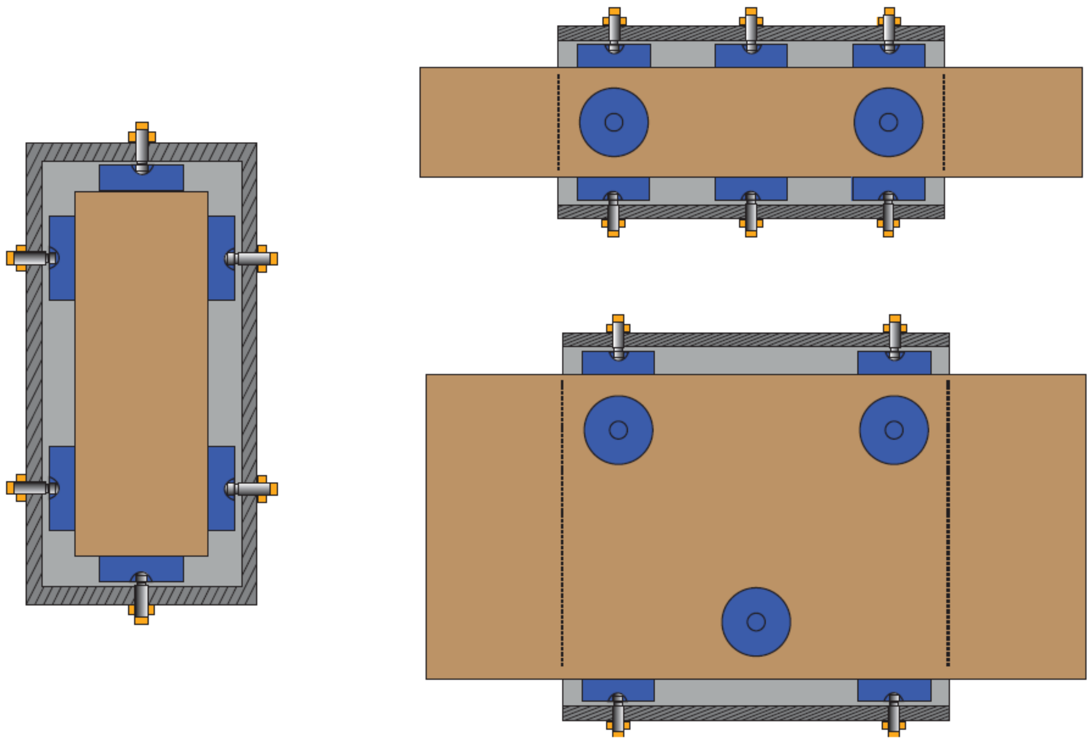
This design has 2x the roll and pitch stiffness and twice the load capacity. The setup and adjustment will be more difficult especially if the housing is relatively stiff. If the housing is not stiff it is more likely to elastically deform.

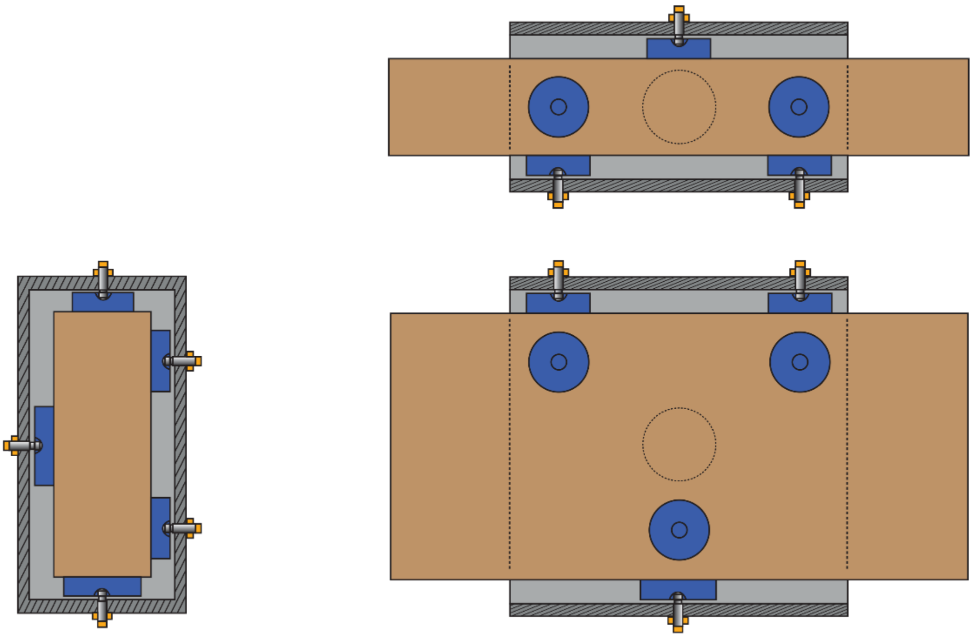


Bearings preloading directly across from each other. Three sets establishing a plane. Two sets establishing a line. 10 bearings are used in this layout.

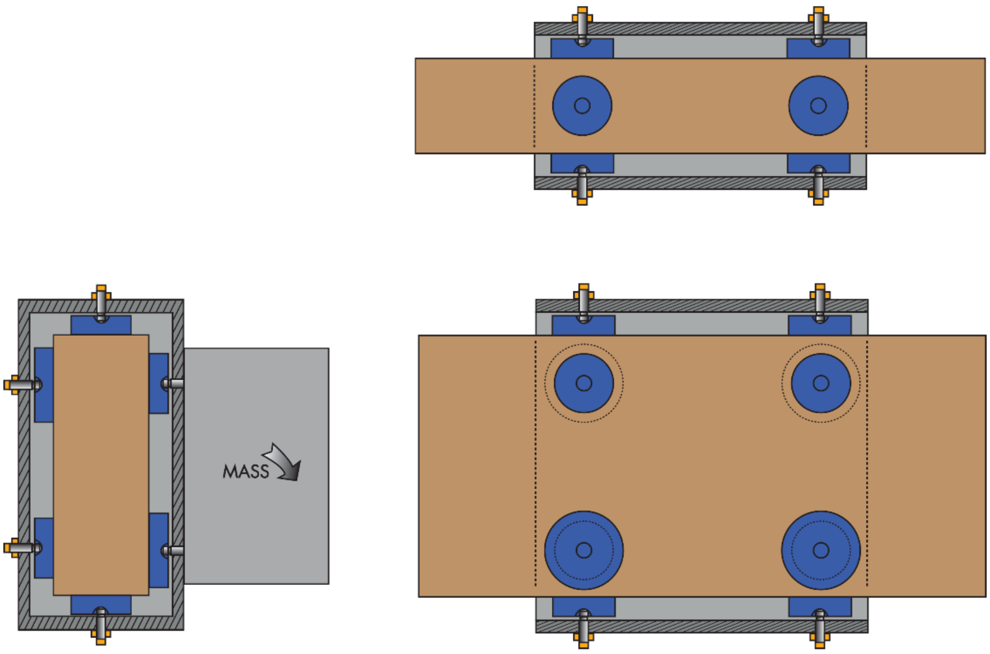


Last update: 2023-06-07

More deterministic in its preload on the 3 bearings establishing a plane and the 2 establishing a line. Very easy alignments, uses less bearings, but sacrifices stiffness. 7 bearings are used in this layout.

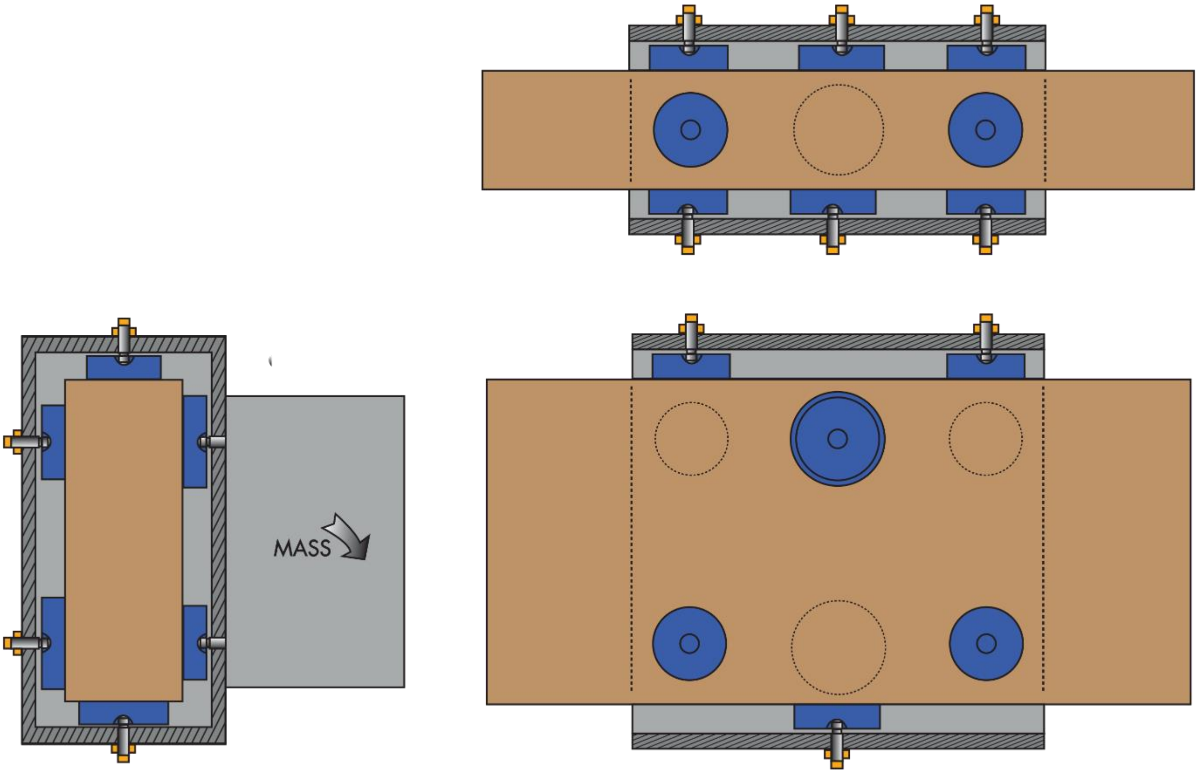


If a large off-axis mass is found in the design you may consider using larger or more bearings in the locations where the weight will bear. Note that if the mass is big enough to require a large difference in bearings or sizes, the slide may not operate without the mass.



Directly opposed bearings with size bias to counteract load. 12 bearings used.

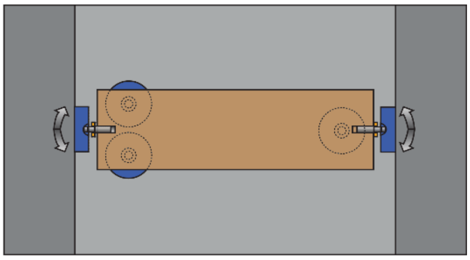
Last update: 2023-06-07



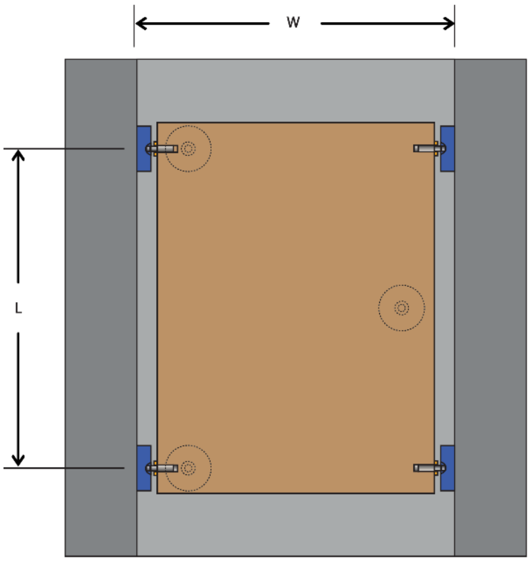
Staggered bearing locations with quantity bias to counteract load. 9 bearings used.

Last update: 2023-06-07

This is a very unstable design. Any lead or lag error between the two sides will result in a yaw force. The higher the preload force the higher the yaw force. Good control engineering may be able to deal with this, using linear motors and encoders on both sides, however it adds cost to the design. This arrangement though is not recommended.

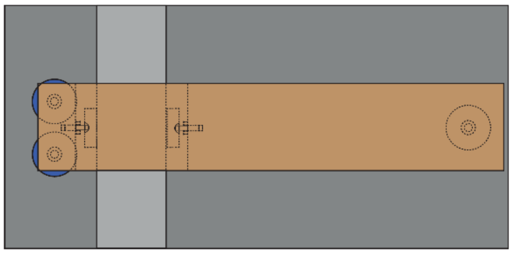


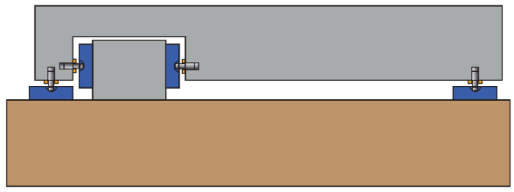
When four bearings are used the situation is much improved, but until L equals or exceeds W the system will be relatively unstable.

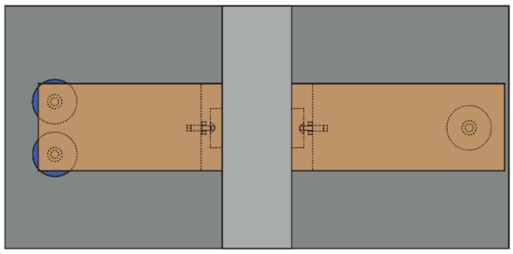


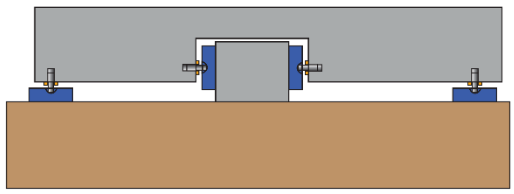
Last update: 2023-06-07

This guidance system is inherently stable, the two bearings will always be trying to find the shortest distance across the guide way. The higher the preload force the higher the squaring force will be.









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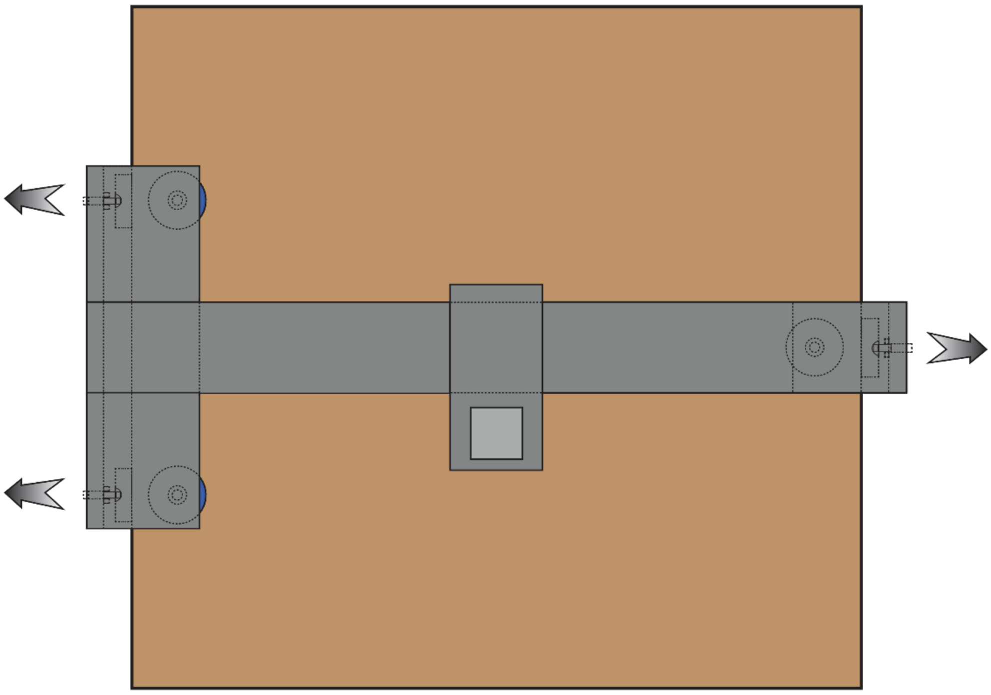
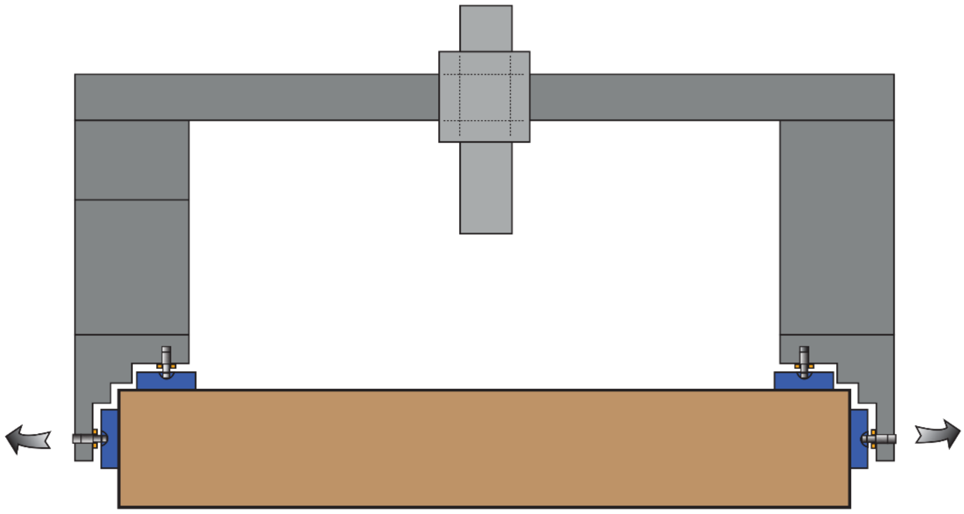
This design suffers from gantry splay.





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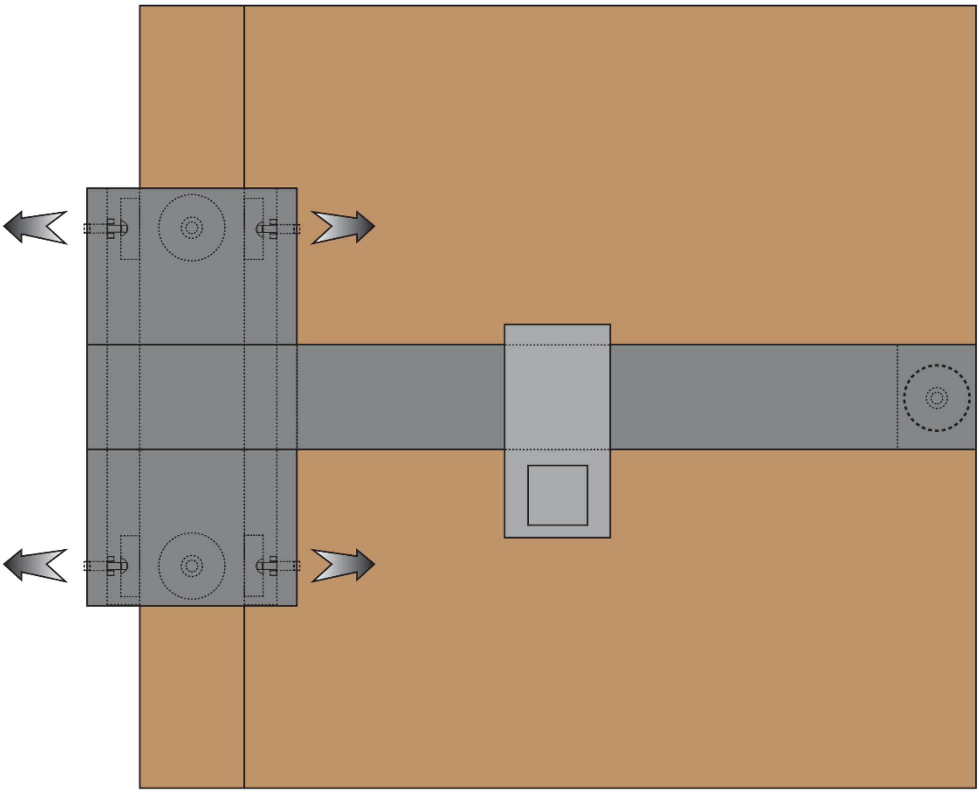
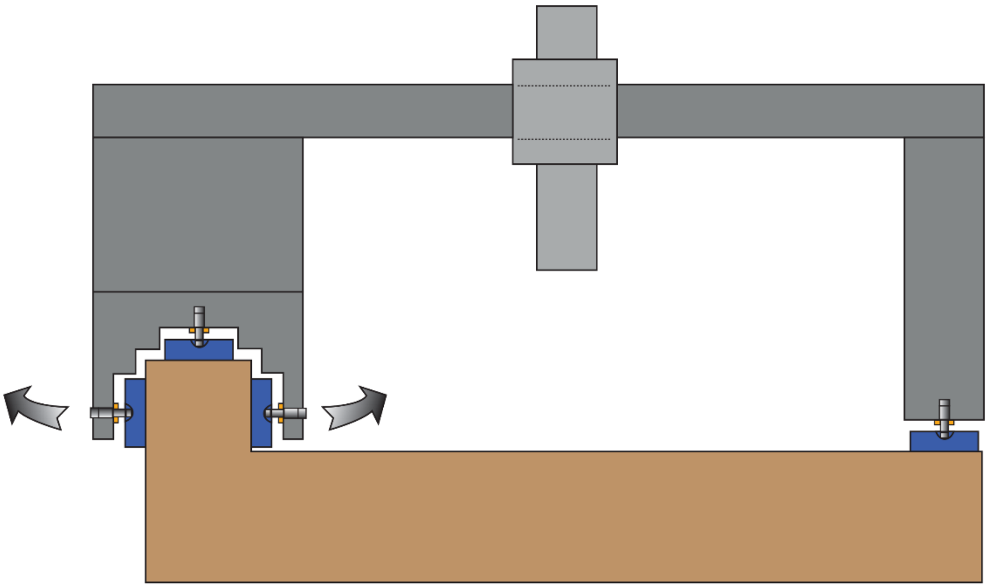
This design has significantly less gantry splay.





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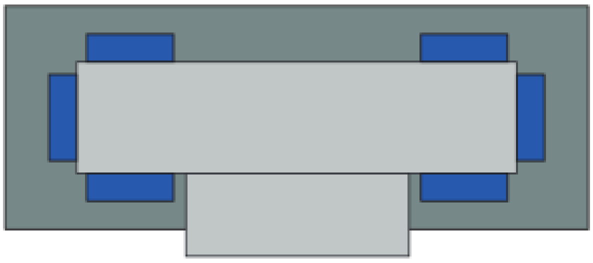
Single rail continuously supported



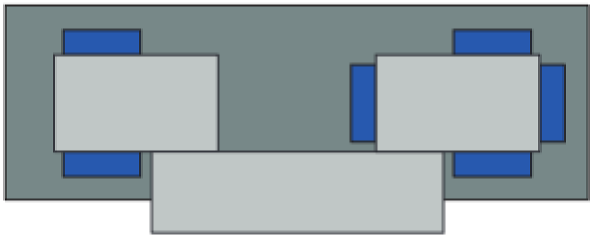
Pro:

Easy to manufacture and align

Con:

Straightness guidance bearings relatively for apart

Double rails continuously supported single rail guidance



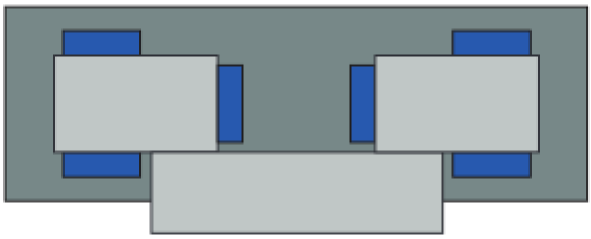
Pro:

Straightness guidance bearings are relatively near each other.

Con:

More difficult alignment for flatness.

Double rails inside edge guidance



Pro:

Center of guidance is center of mass

Con:

Difficult to align two rails parallel

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Dovetail continuously supported:

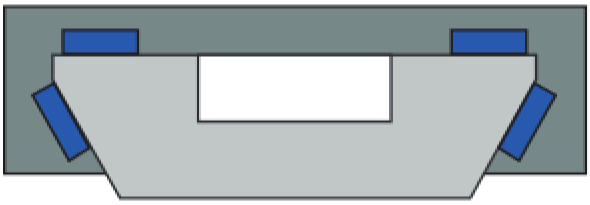
Pro:

Fewer bearings required.

Con:

Lower bearings must be larger to achieve same pre-load.

Metrology of the guide bar can be difficult.



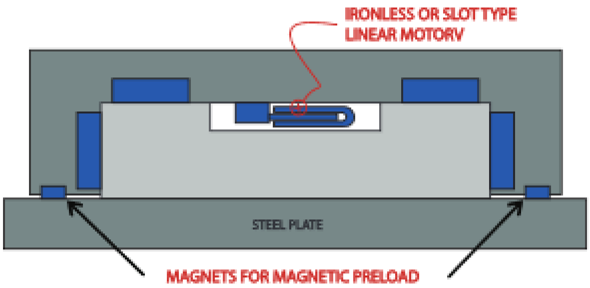
Magnetic preload single guide

Pro:

Does not need to be mounted on surface plate.

Con:

Guide assembly often from two materials.



Magnetic preload axtrusion guide

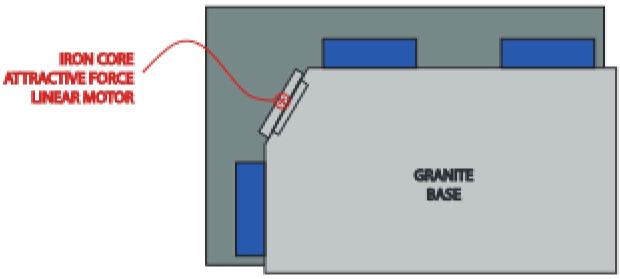
Pro:

Only two precision surfaces.

Attractive force from one linear motor preloads flatness and straightness bearings.

Con:

User license required.



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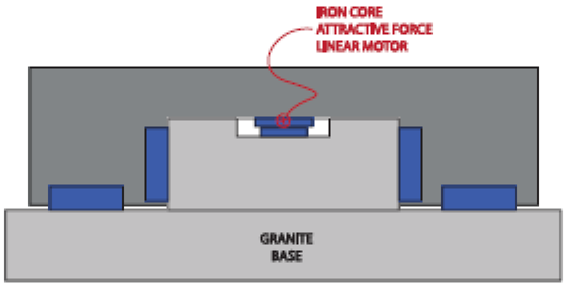
Magnetic preload single guide



Pro:

Widely spaced load carrying bearings.

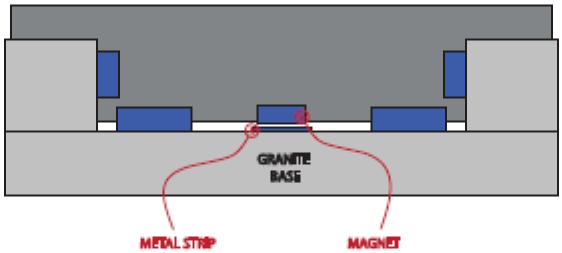
Does not require magnetic strips.

Con:

Requires mounting on granite base.

Use of iron core motor for pre-load may result in cogging.

Magnetic preload single guide



Pro:

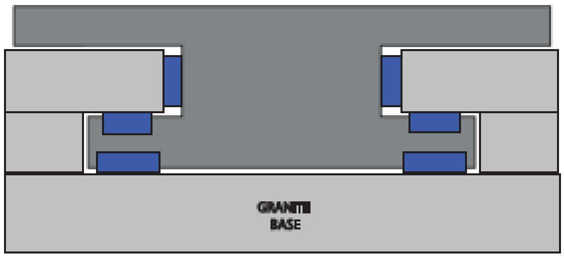
Widely spaced load carrying bearings.

Con:

Difficult alignment of vertical guides.

Straightness guidance bearings far apart.

Double rail keeper inside guide



Pro:

Flatness guidance from base granite.

Con:

Difficult alignment of straightness guide rails.

More deflection of keeper.

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Double rail keeper outside guide

Pro:

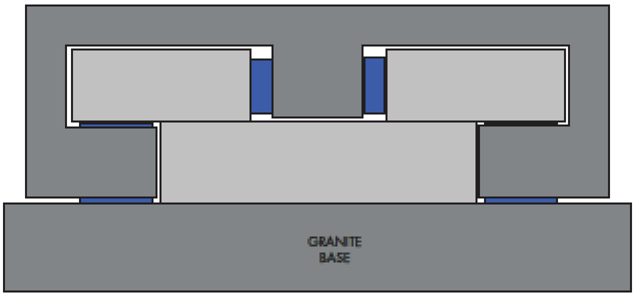
Flatness guidance from base granite.

Less deflection of keeper.

Con:

Difficult alignment of straightness guide rails.

Double rail keeper



Inside Dovetail guide

Pro:

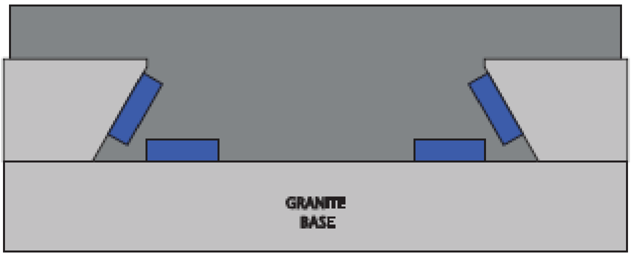
Less precision surfaces.

Suitable for wide stages.

Con:

Doubly difficult alignment!

Minimal pre-load capability.



Female V and Flat

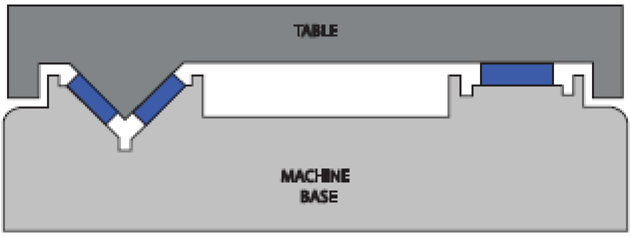
Pro:

Quasi Kinematic Design.

Con:

Requires gravity pre-load.

Guide ways integral with base.



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Male V and Flat

Pro:

Quasi Kinematic Design.

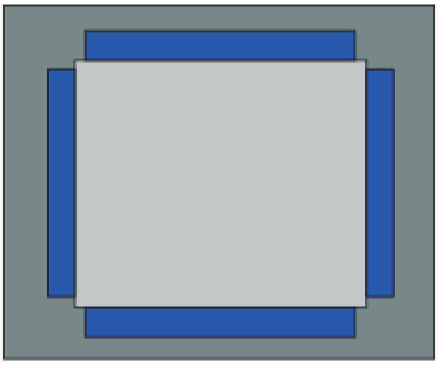
Removable guide surfaces.

Con:

Requires gravity pre-load.

Square Guide.

Full Bearing



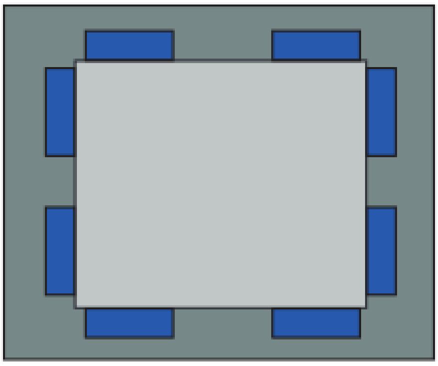
Pro:

High Load Capacity.

Con:

Housing Distortion.

Square Guide Split Bearing



PRO:

High roll capacity.

CON:

Requires more bearings.

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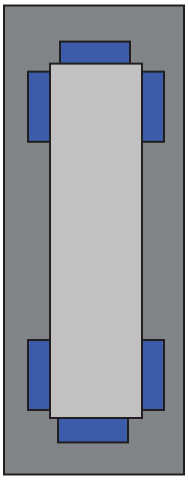
Rectangular Guide

Pro:

Less beam deflection.

Con:

Requires more vertical space.



Single Rail End Support

Pro:

Easy to Manufacture and Align.

Con:

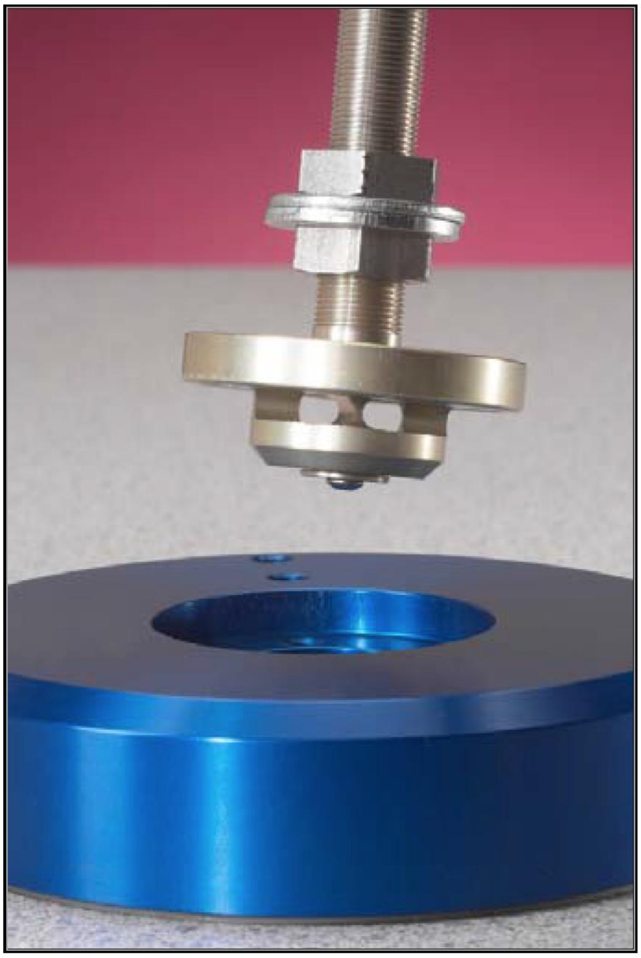
Straightness Guidance bearings relatively far apart.

Last update: 2023-06-07

12 VPLs

12.1 Vacuum Preloaded Air Bearing Technology

Vacuum preloading of air bearings is a technique where the fundamental principle is to create a vacuum under the bearing structure, effectively preloading it against the guide surface. The vacuum preloading technique coexists with the air bearing surfaces positive pressure, allowing for simultaneous preloading against a surface, all the while preventing the bearing from making contact with the guide. The trick to vacuum preloading is to realize that air bearing lands, or any inactive surface on the same plane as the bearing face, can serve as a vacuum seal. It is counter intuitive that a positively pressurized air gap can also act as a vacuum seal, but the combination actually works very well, especially once you consider that a VPL may consume less than 5 cubic feet of air per hour, and less than half of that will find its way into the vacuum, it is easier to conceptualize. In addition, the small flow into the vacuum can be dramatically reduced when ambient pressure grooves between active air bearing areas are combined with the seal lands. The preload force is created in the center area where vacuum is drawn, causing the outside atmosphere to effectively press down on the bearing, creating a preload force equal to the projected area of the vacuum pocket multiplied by the pressure differential. It is relatively easy to create a vacuum of -10PSIG which is enough to apply a significant preload force to a bearing. For example, a large monolithic VPL with 12 square inches of surface area can create over 800 pounds of preload force and a stiffness of well over 2 million pounds per inch, using only a single pound of payload. The advantage of vacuum preloading is that it creates a preloading force on the bearing without the need for additional mass. This technique is often used when high acceleration stages need fast settling times. This technique is highly advantageous when high acceleration stages also require low settling times. By guiding XY motion off a precision plane, the Abby errors, which define the magnification of angular distance over a distance, may be eliminated. This technique also eliminates tolerance build-ups from stacked linear axes, providing for exceptional flatness of motion. Finally, VPL's allow for simultaneous preloading over a plane on both x and y axes without needing a completely metal guideway, as would be required with magnetic preloading.



A common design for vacuum preloaded air bearings has the positive pressure air bearing land in the center with the vacuum around the perimeter. A drawback of this design is that it draws air (and debris) in from the environment surrounding the bearing, acting somewhat like a vacuum cleaner. A more refined VPL design has the positive pressure air bearing land around the perimeter of the bearing, creating the seal to contain the vacuum in the center

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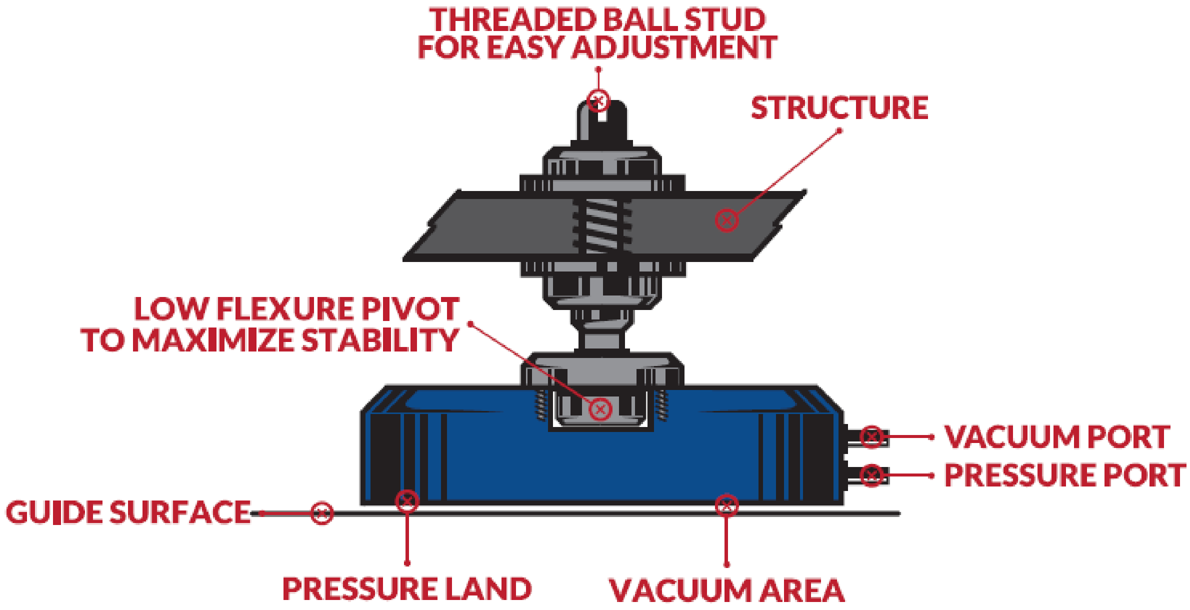
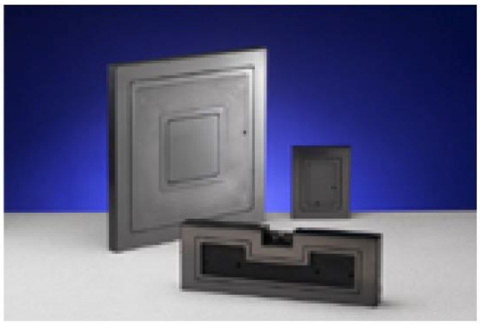


of the bearing. By positioning the air bearing land around the perimeter, the continual positive flow of air to ambient atmosphere actively keeps dust and contaminants away from the bearing surface. While vacuum preloaded air bearings can be designed with either orifice or porous media bearing technology, porous media bearings have a distinct advantage in that they won't damage the guideway surface should there be an inadvertent loss of air. In this situation, the porous media material itself will act like a plain bearing, making porous made based VPL's easier to use and more robust than orifice designs. Porous media VPL's are available as off the shelf modular products, or as custom components which can be manufactured integral to other structural components (under a Z stage, for example). Modular VPL's are mounted with flexures capable of providing self-alignment to the bearing faces, as well as height adjustment without hysteresis or friction. Custom VPL's can also be bonded in place using a process, patented by IBS, which produces a precision stage without expensive machining. This technique is used to great effect in the X and y stages of the Electroglas 300mm wafer Prober. A large, square VPL is also employed under the Z stage, allowing it to float over the granite base. By adjusting the vacuum and air pressure, fly height and stiffness can be precisely optimized to the individual application. In this instance, air film adjustability can be used for focusing, squaring and sub-micron vertical positioning over a range of 20 microns.



12.2 Kinematics and elastic averaging

Kinematic designs employ the theory of exact constraint, which is to say that three points describe a plane, two points describe a line and one point describes a position on the axis of motion defined by the plane and the line. An advantage to kinematic designs is that by knowing the location and stiffness of the support points in a kinematically supported structure, closed-ended mathematical equations may be used to model and predict the system's characteristics, making the system "deterministic". Modular vacuum preloaded air bearings mounted on flexures are easily utilized to support kinematic structures.

By contrast, the practice of preloading air bearings against each other on opposite sides of a beam is an example of “elastic averaging”. In this example, 4 bearings (two on either side) describe a line, but because the two sides of the beam are most likely not perfectly parallel, it is more difficult to predict or define error motions. Furthermore, changes in size between the bearing structure and the beam due to thermal expansion can cause over constraint. A large monolithic VPL mounted on a plane is also an example of elastic averaging.

Three small VPLs, flexure mounted to a piece of aluminium tooling plate would create an inexpensive and kinematically correct stage. The threaded flexures would allow for adjustment and squaring the base plate to another reference, no further machining would be required and assembly would be straightforward. Additionally, any distortions due to the pressure and vacuum forces are isolated to the bearing itself, and are not transmitted through the flexure and into the structure.

Conversely, a single monolithic VPL would have higher load stiffness and load capacity, though it would be a much larger surface to make flat. This in turn would require a greater degree of craftsmanship in manufacture and assembly, and the structure itself would need to be stiff enough to withstand the distortion from the vacuum and pressure forces. Also, this can make integration with other stages more complicated. While this method does not produce deterministic motion of the plane, it does work to average out errors in the guide plane.

Kinematic:

- Deterministic: A deterministic system involves no randomness in the development of future states of the system. A deterministic model will always produce the same from a given set of initial conditions.
- Does not require precision machining
- Easier manufacturing
- Stiffness and load capacity limited

Elastic Averaging:

- Non-deterministic
- Requires precision machining
- More difficult to manufacture
- High stiffness and capacity

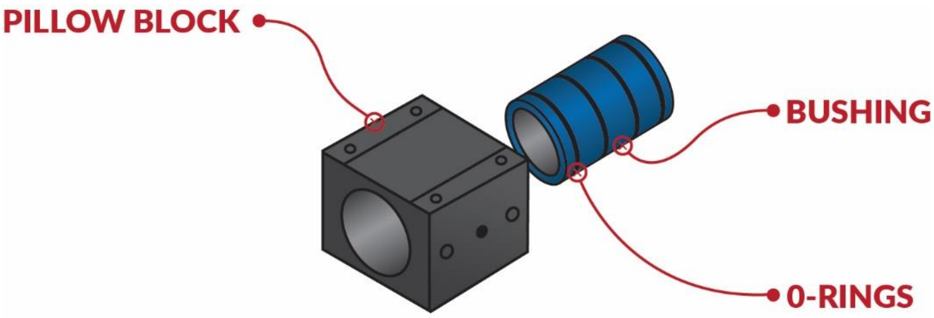
Last update: 2023-06-07

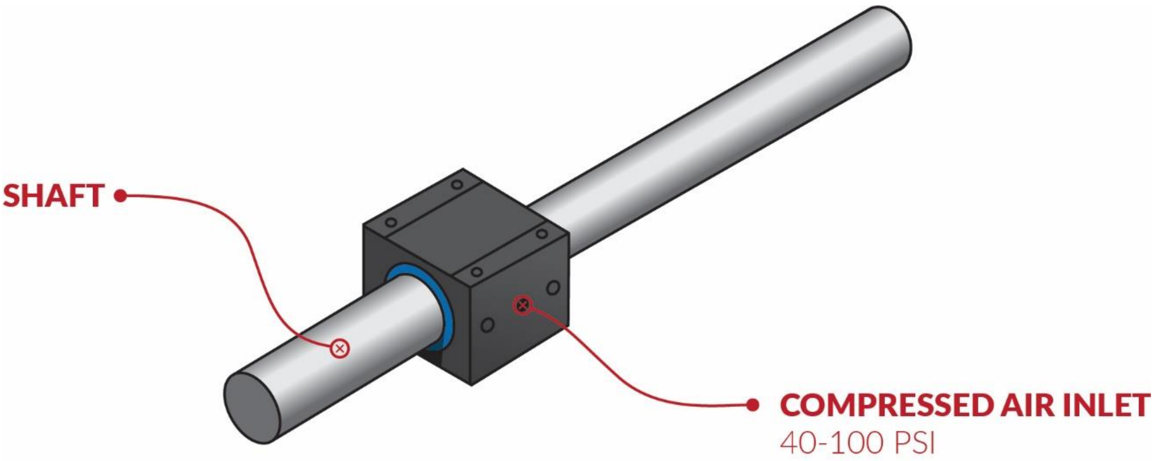
13 Air Bushings

13.1 Air Bushing Installation

Inspect the inner diameter (ID) of the pillow block for any burrs or sharp edges, and be sure the O rings are seated properly within their grooves on the air bushing housing. Wet the O rings and the bore with isopropyl alcohol just prior to inserting the bushing into the bore.

Supply clean, dry compressed air between 40 and 100 psi into the pillow block. With a clean cloth or towel and isopropyl alcohol, wipe the shaft to be inserted into the bushing. Carefully insert the shaft into the bushing with the air pressure on.

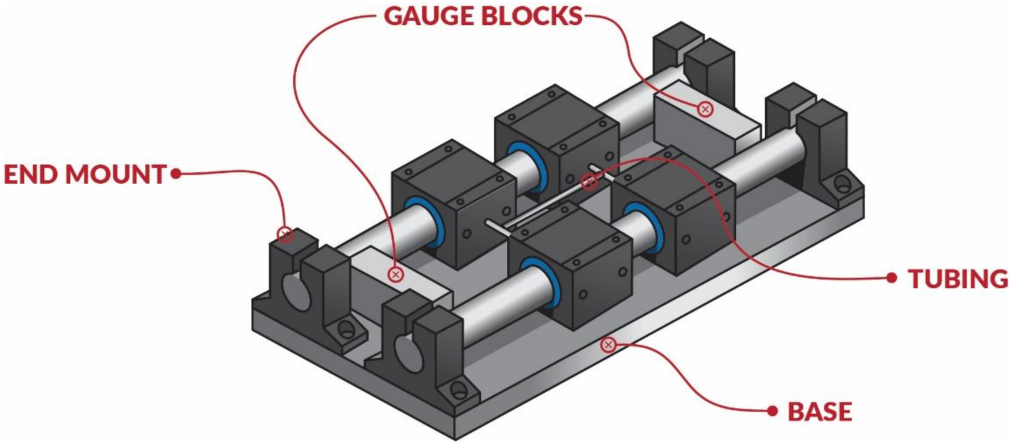




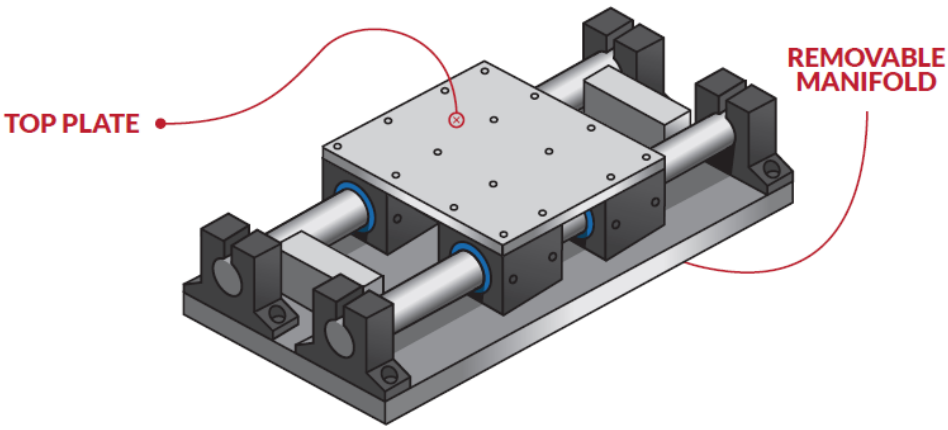
Last update: 2023-06-07

13.2 Assembling an Air Bushing Slide

Attach end mounts to the shaft while the bushings are on the shafts with light screw pressure. Using gauge blocks between the shafts, tighten the end mounts to the base, which will establish parallelism of the shafts. Tighten the end mounts on the shaft and recheck parallelism of the shafts. In this process it may be necessary to loosen and retighten the end mounts to the base, in order to ensure parallelism.

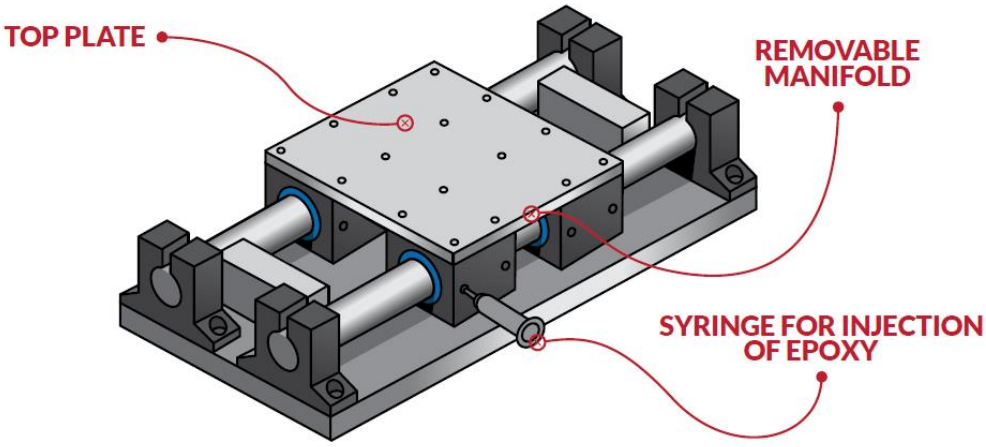


With air pressure applied, align and bolt the top plate to the pillow blocks, and check to make sure the stage froats freely over its entire travel distance. The O rings allow for 0.002" of misalignment and should provide enough compliance to compensate for parallelism errors in the shaft or out of flatness of the top plate. Please note this is only one example of an assembly procedure.



Last update: 2023-06-07

It is possible to eliminate compliance of the O rings by potting the bushings into the pillow block housings with epoxy, although this is by no means required. The pillow block housings feature holes 180 degrees apart, aligning axially with the center of the two O ring sets. With the air pressure on, inject epoxy into one side until it comes out the opposite side, and then tape over the injection ports and vents until the epoxy is allowed to cure, still with air pressure on. This procedure is useful where high stiffness is required and the shafts can be aligned with a high degree of precision.



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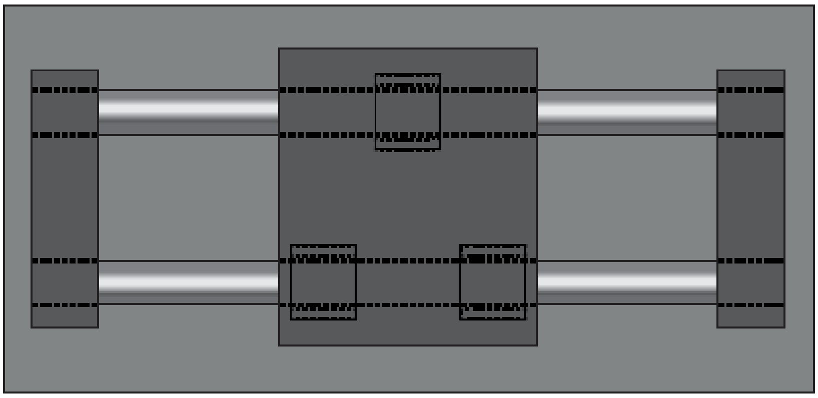
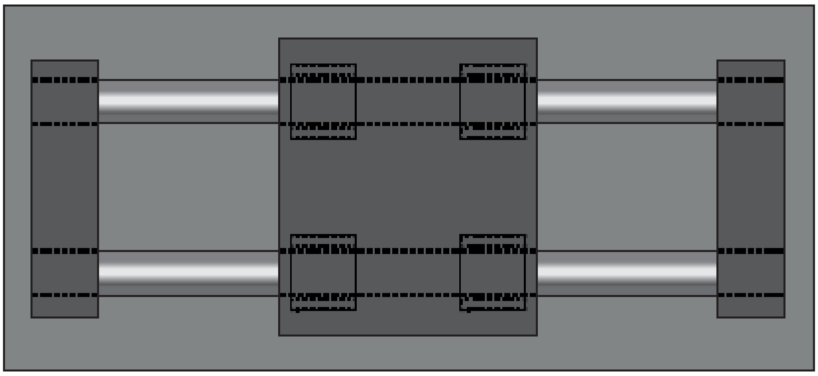
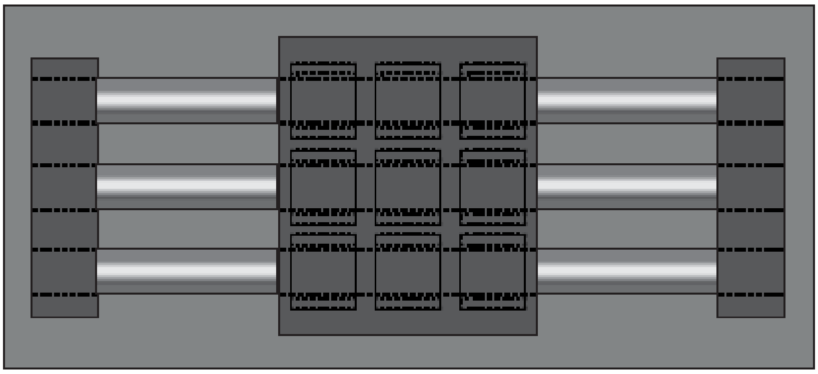
13.2.1 Typical Configurations



Three air bushings are all that is required to constrain five axis of motion.



Four air bushings is the most typical configuration for creating a linear slide from air bushings.



In cases where higher load capacity is required extra bushings can be added and or extra shafts can be used.

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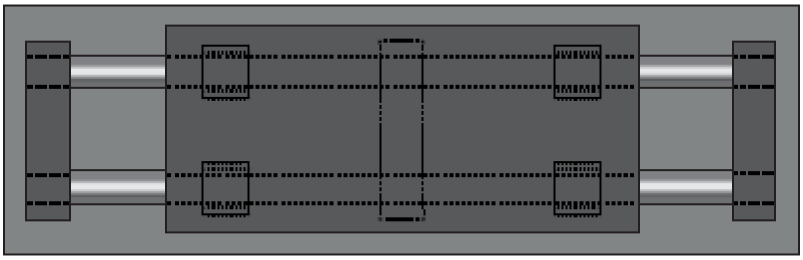
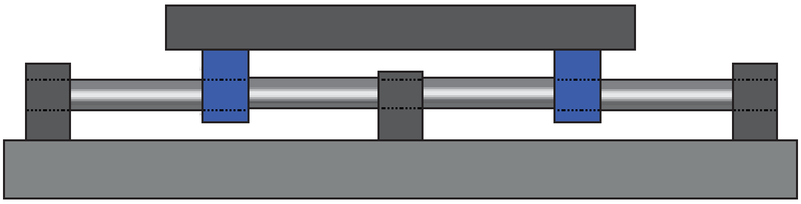
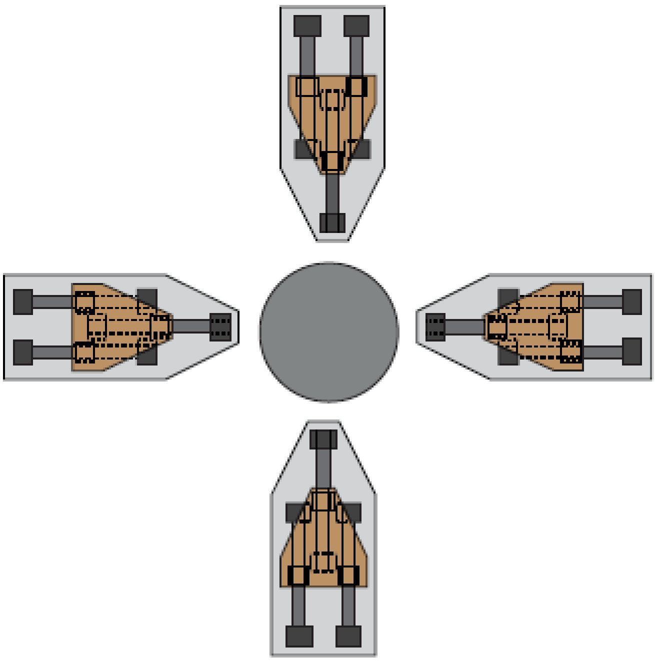




As the deflection of the end supported shafts tends to be the major source of compliance, especially in longer stages, center supports significantly increase stiffness (if the application allows).



Air bushings stages lend themselves to arraying themselves around a Rotary table.

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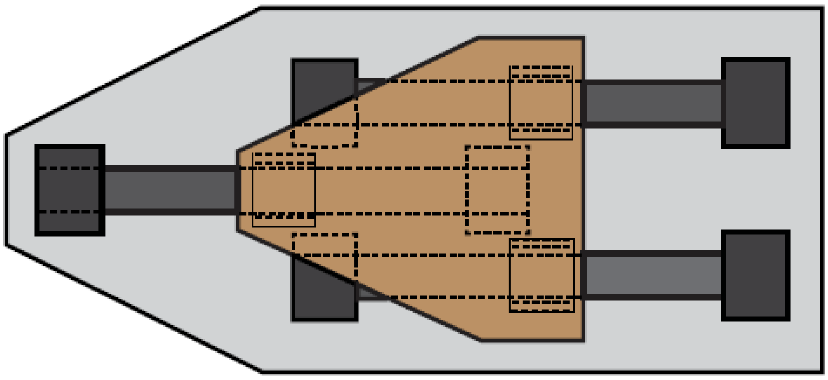
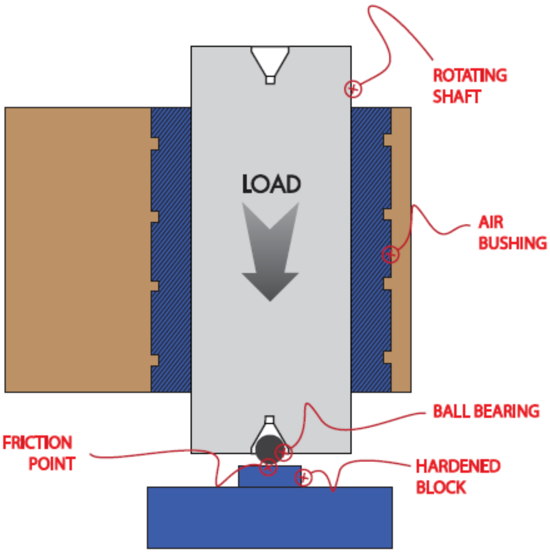
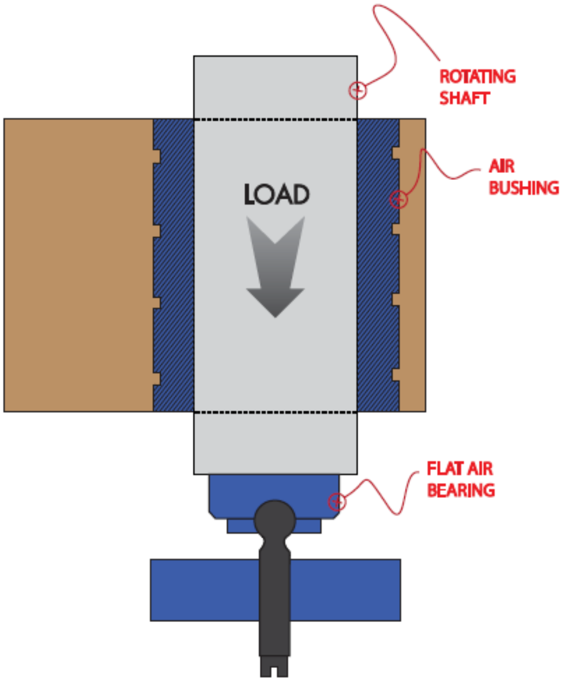


Very high stiffness low-profile stages can be constructed using bushings. Multiple bearing sets and shafts can make for difficult assembly operations. Replication techniques can be employed that greatly minimize this problem.

In cases were the rotating shaft has been ground on an OD grinding machine the shaft will likely have an accurate conical center in it. A ball bearing can be glued into this conical seat and then run against a hard end surface such as a micrometer anvil. This does result in some Coulomb friction but the amount of friction is amazingly small.





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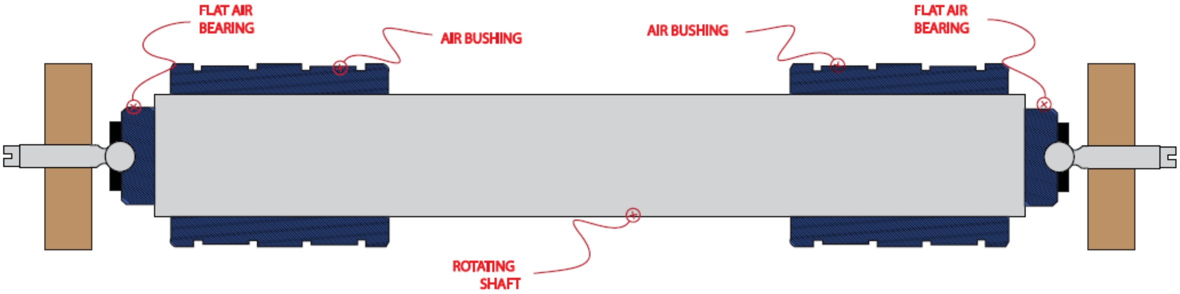

Common application for creating zero friction pulleys for counter balances or Web handling.

Last update: 2023-06-07

14 Rotary tables

The spinning artefact, or spindle is the most critical component to consider when you are trying to achieve the lowest possible error motions in a rotational system. For these applications, ultra-precision machining techniques are recommended. Fortunately, conventional precision turning and grinding can achieve excellent results, as the two critical surfaces (radial and thrust) can be finished in a single chucking, although care must be taken to ensure the spindle is not distorted by chucking forces. IBS has the capability to supply ultra-precision, diamond turned artefacts for our air bearing customers.

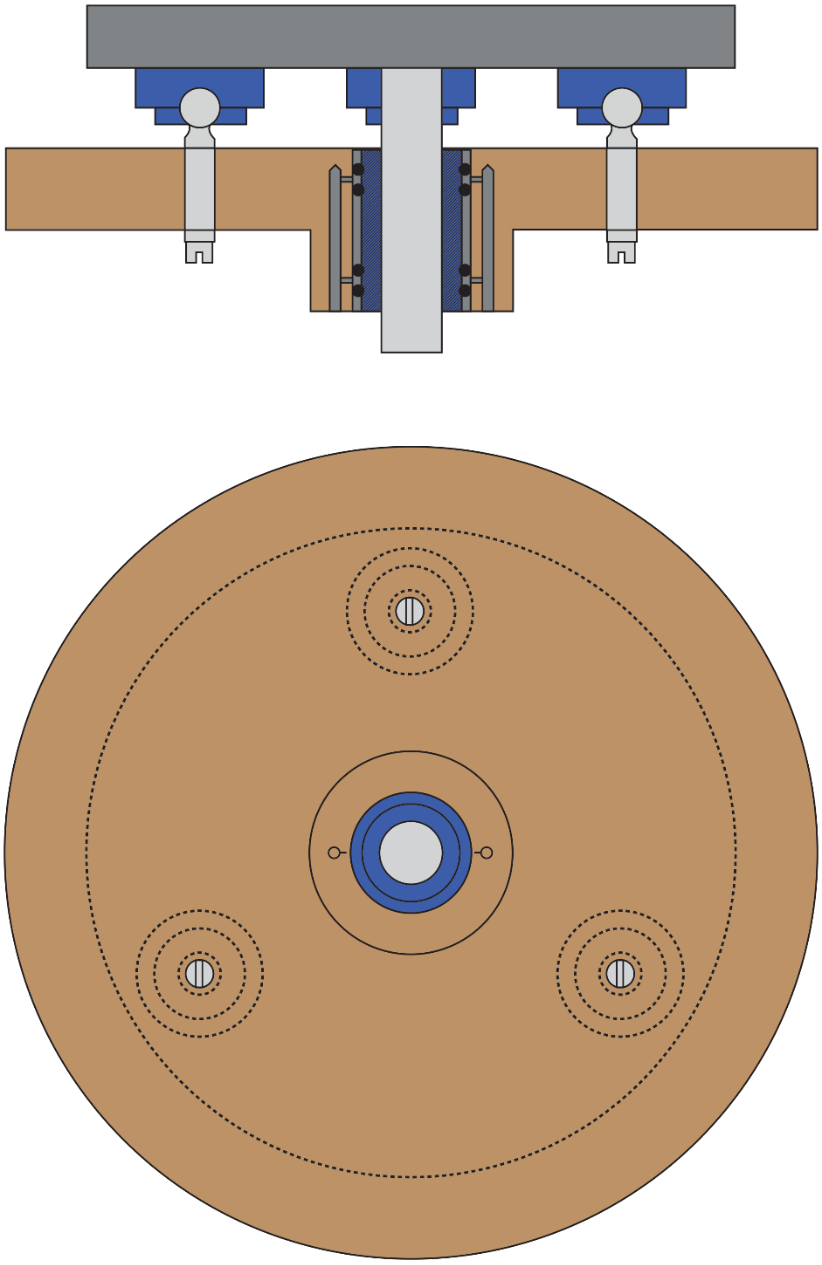

Figure 19 Rotary Table

Last update: 2023-06-07

Ball studs can be used to adjust total height and the angle of the axis of rotation. Once set, the bushing can be bonded to increase radial stiffness. The O rings allow the bushing to align itself with the spindle axis, and since three conical seats in the plate will describe a plane, an arrangement of this type may be situated without the need for height adjustment, since it is kinematically exact.

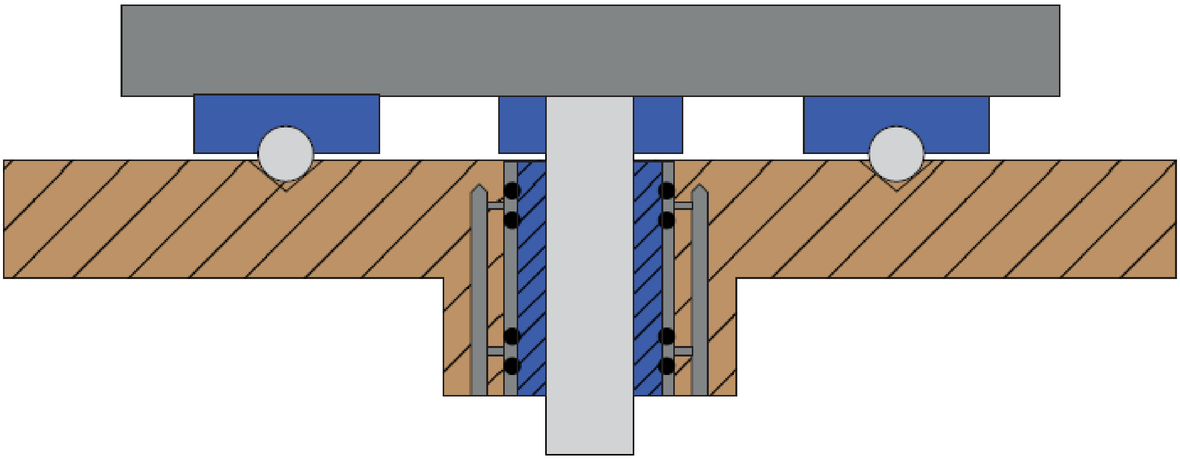

Figure 20 Rotary Table Air Bearings

Last update: 2023-06-07

Part V: Additional Information

15 Air Supply

Because air bearings don’t need to be supplied from a pressurized tank, you can pull from the atmosphere so long as you pass your air supply through the proper combination of filters we recommend. If the air bearing is operating in a vacuum, or in an ultra-clean environment like a clean room, pumped or scavenge grooves can completely eliminate leakage of air or particles into the vacuum or environment, although it should be noted that per internal IBS testing, our unscavenged air bearings meet 3 cleanroom compliance standards.

Air bearings should be supplied with air which is relatively free of particulates, water and oil. Please reference the below table of ISO air quality classes for what constitutes “relatively clean”.

		Solid Particulate				Water		Oil
	ISO85753-1:2010 Class	Maximum number of particles per m3 Concentration			Concentration	Vapor	Liquid	Total Oil (aerosol, liquid and vapor)
		0.1 - 0.5 micron	0.1 - 1 micron	1 - 5 micron	mg/m3	Pressure Dewpoint	g/m3	ppm(mg/m3)
	1	≤ 20,000	≤ 400	≤10	-	≤ -94°F (-70°C)	-	0.008 (0.01)
	2	≤ 400,000	≤ 6,000	≤100	-	≤ -40°F (-40°C)	-	0.08 (0.1)
Recommended >	3	-	≤ 90,000	≤1,000	-	≤ -4°F (-20°C)	-	0.83 (1)
Minimum specs >	4	-	-	≤10,000	-	≤+37°F (3°C)	-	4.2 (5)
	5	-	-	≤100,000	-	≤+45°F (7°C)	-	-
	6	-	-	-	≤ 5	≤+50°F (10°C)	-	-

Please turnover.

Last update: 2023-06-07

Please note different types of air bearings are sensitive to different types of contamination. For example, porous media bearings are not sensitive to particulates like pieces of Teflon tape, sealant, or liners shedding from the inside of fatiguing air tubes. In fact, you could pour sand into a porous media air bearing air supply port with no derogatory effects. While this would be catastrophic for an orifice or step type compensated bearing, the porous media bearing is unaffected, since the porous media acts as a sub-micron filter. While oil contamination may be more easily cleaned out of an orifice bearing, water contamination can be easily corrected by introducing clean dry air to the system over time, providing that the system components are not subject to oxidation.

Last update: 2023-06-07

16 Measuring Flow

When measuring flow, we have to start from the principle that air is a compressible fluid. If one cubic foot of air at atmospheric pressure is compressed to 60 psi, or about 4 times atmospheric pressure, it will occupy less than half of a cubic foot of air. This nonlinear relationship requires a correction factor based on pressure, which we then apply to flow measurements of pressurized air when using venturi based flowmeters. Venturi (visi-float) based flow meters may say SCFH on the side, but this only applies when the exit side of the flow meter is at ambient pressure. Mass flow meters, on the other hand do not require corrections, since they count molecules, but are nearly 10 times the cost of conventional flow meters, and may take time to settle in for accurate readings.

Note the century flow meter clearly states standard cubic feet per hour (or SCFH) on the gauge, and please be advised this only applies if the exit side of the flow meter is at atmospheric pressure. In an air bearing, flow meters are employed in the supply line to the bearing, so the exit pressure from the gauge is likely to be in the area of four to six times as high as ambient atmospheric pressure. In this case, flow is measured in cubic feet per hour gauge, or CFHG. When CFHG units are used, there should always be a pressure associated with it. It is only SCFH which is presumed to be at atmospheric pressure.

Last update: 2023-06-07

17 Flow

Q2 = Q1 * SQRT (P2/P1)

Q1 = Observed flow meter reading (CFHG)

Q2 = Actual flow corrected for pressure (SCFH)

P1 = Standard atmospheric pressure, 14.7 PSI

P2 = Actual pressure, 14.7 PSI + pressure in PSI inside flow meter.

CFHG = Cubic Feet per Hour Gage

SCFH = Standard Cubic Feet per Hour

SCFM = Standard Cubic Feet per Minute

@60 PSI multiply CFHG by 2.25 to get SCFH

@80 PSI multiply CFHG by 2.53 to get SCFH

@120 PSI multiply CFHG by 3.027 to get SCFH

18 Plumbing

Plumbing air to multiple air bearings is relatively simple; you may run the supply lines either in series or individually. It is most common to have manifolds on each axis, which are then plumbed in series. Other bearings can be on the same manifold, or plumbed individually, and care should be taken to use larger tubing for the manifolds, and smaller tubing for individual bearings.

IBS provides tubing and assorted fitting types as a convenience to our customers. Please visit our website at www.ibspe.com for more information. Quality tubing and fittings save both time and money, preventing the need to deal with possible leaks and compatibility issues.

Last update: 2023-06-07

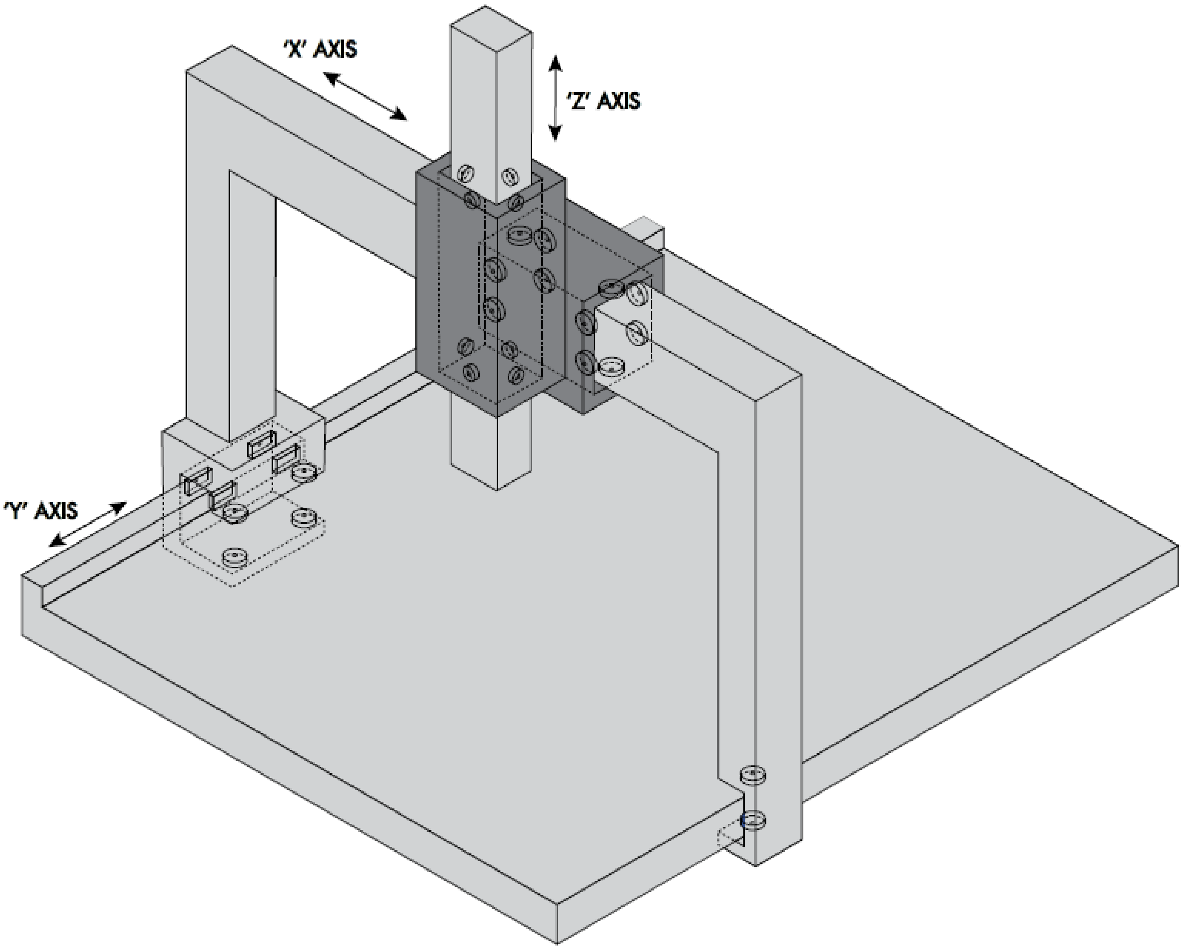

Figure 21 Typical Bearing Layout for a CMM

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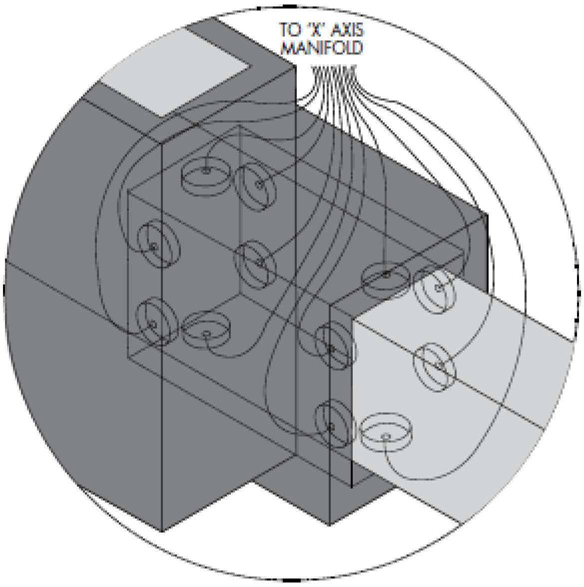

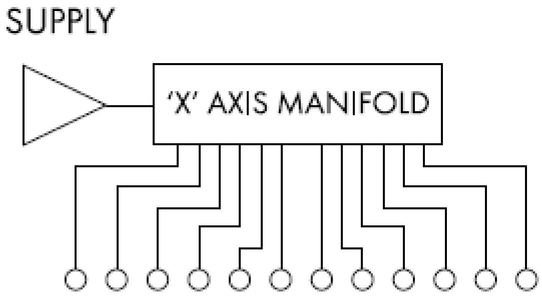

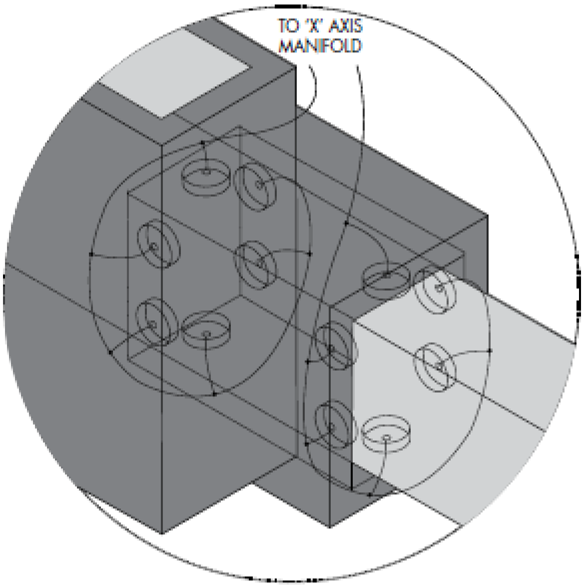

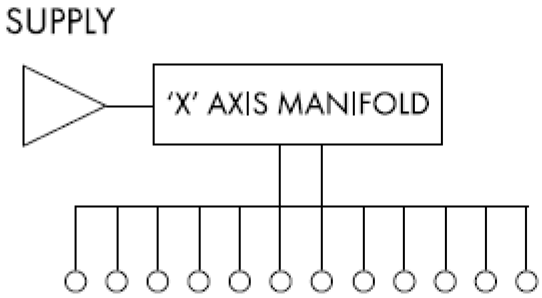

Figure 22 Options for connecting air supply to air bearings

19 Air Flow through the Bearing Gap

Airflow through an air bearing gap is quite sensitive to the size of the gap, following a cubic function with relationship to the size of the gap. As an example, a two inch diameter bearing with 75 pounds of load would consume 4 standard cubic feet per hour (SCFH) at 200 micro inches of lift. For this bearing to carry the same load at 400 micro inches of lift, 64 SCFH would be required. From this relationship, we can easily see how a smaller gap keeps the restriction high, reducing flow and power requirements. Smaller gaps mean less airflow, which means less air which must be cleaned and dried, and thus reducing the cost of ownership. It is interesting to note how this effect distinguishes porous and orifice type bearings when comparing the pitch moment stiffness of an individual bearing. As orifice bearings are dependent on flow across the face of the bearing, an angular change in the gap will cause fatal instability in the bearing, and it will ground. As an example which we previously discussed, when one side of the gap becomes large and the other side becomes small, an unstable situation is created where the available air beneath the bearing will rapidly depressurize and flow towards the path of least resistance, which in this case is the larger gap and away from the area which needs it most, in this case the smaller gap. Bycontrast, the porous bearing still has pressure issuing from the smaller gap, providing it with higher tilt moment capacity and stiffness.

This same effect is why uncompensated journal bearings do not work. At first, we might think that by pressurizing an annular groove, the air pressure would equalize and support the shaft, but in fact the shaft presses against one side, closing off that side of the gap completely. Now you have one side of the journal bearing under twice the gap, creating even less restriction than an even layer all the way around the shaft, thereby grounding it

Last update: 2023-06-07

20 Air Supply requirements

20.1 Air Quality

The compressed air which you supply an air bearing with must be properly cleaned and dried. Air bearing performance and useful lifetime greatly depends on the quality of your air supply. An efficient system will ensure minimal pressure loss as well as the removal of contaminants such as water, oil, dirt, rust and other foreign particles. Particles are less of a concern for affecting the performance of IBS Porous Air Bearings, but water and oil can have substantially deleterious effects. In order to ensure the specified performance and useful lifetime of the bearings, we recommend the following minimum criteria for air quality be met.

		Solid Particulate				Water		Oil
	ISO85753-1:2010 Class	Maximum number of particles per m3 Concentration			Concentration	Vapor	Liquid	Total Oil (aerosol, liquid and vapor)
		0.1 - 0.5 micron	0.1 - 1 micron	1 - 5 micron	mg/m3	Pressure Dewpoint	g/m3	ppm(mg/m3)
	1	≤ 20,000	≤ 400	≤10	-	≤ -94°F (-70°C)	-	0.008 (0.01)
	2	≤ 400,000	≤ 6,000	≤100	-	≤ -40°F (-40°C)	-	0.08 (0.1)
Recommended >	3	-	≤ 90,000	≤1,000	-	≤ -4°F (-20°C)	-	0.83 (1)
Minimum specs >	4	-	-	≤10,000	-	≤+37°F (3°C)	-	4.2 (5)
	5	-	-	≤100,000	-	≤+45°F (7°C)	-	-
	6	-	-	-	≤ 5	≤+50°F (10°C)	-	-

Last update: 2023-06-07

20.2 Filtering and Drying Compressed Air for Air Bearings

General purpose filters are used to remove the bulk of particles before they get downstream and clog the finer, coalescing filter unnecessarily. The coalescing filter is used to remove oil and liquid water, as well as any particles too small to be filtered out by the general purpose filter. The desiccant dryer is then used to remove any water vapor before it can condense. A full line of air filters, regulators, kits and supplies are available on our website.

Component	Dirt Particle Size in Microns	Water Vapor Dew Point * F @ 100 PSIG	Oil & Liquid Water mg/m
General Purpose Filter	25	N/A	N/A
Coalescing Filter	0.1	N/A	0.5
Desiccant Dryer	N/A	-40	N/A

Figure 23 Filtering and Drying Compressed Air

Last update: 2023-06-07

20.3 Flow Equivalents

1 Cu. Ft./Hr.	
Cu. Ft./Min.	0.166
LPM	0.4719
LPH	28.316
CC/Min.	471.947
CC/Hr.	28317
Gal./Min.	0.1247
Gal./HR.	7.481

1 CC./Min.	
CC/Hr.	60
Cu. Ft./Min.	0.000035
Cu. Ft./Hr.	0.0021
LPM	0.001
LPH	0.06
Gal./Min.	0.00026
Gal./Hr.	0.0159

1 CC./Min.	
CC/Hr.	60
Cu. Ft./Min.	0.000035
Cu. Ft./Hr.	0.0021
LPM	0.001
LPH	0.06
Gal./Min.	0.00026
Gal./Hr.	0.0159

1 CC. Ft./Hr.	
CC/Min	0.0167
Cu. Ft./Min.	0.0000005
Cu. Ft./Hr.	0.00003
LPM	0.000017
LPH	0.001
Gal./Min.	0.000004
Gal./Hr.	0.00026

1 LPM	
LPH	60
Cu. Ft./Min.	0.035
Cu. Ft./Hr.	2.1189
CC/Min.	1000
CC/Hr.	60,002
Gal./Min.	.264
Gal./HR.	15.851

1 LPH	
LPM	0.0166
Cu. Ft./Min.	0.035
Cu. Ft./Hr.	16.667
CC/Min.	1000
CC/Hr.	0.004
Gal./Min.	0.264
Gal./HR.	0.00059

1 Gal./Min.	
Gal./Hr.	0
Cu. Ft/Min.	.1337
Cu. Ft./Hr.	8.021
LPM	3.785
LPH	227.118
CC./Min.	3,785,415
CC./Hr.	227,125

1 Gal./Hr.	
Gal./Min.	.0167
Cu. Ft./Min.	.002
Cu. Ft./Hr.	.1337
LPM	.063
LPH	3.785
CC./Min.	63.069
CC./Hr.	3785